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Digital transformation and public health emergency management capacity: epidemic pressure as a constraint and innovation capacity as an enabler

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Background: Digital transformation is increasingly embedded in public health systems, but its contribution to emergency management may depend on the conditions under which digital resources are deployed. Existing research has focused primarily on specific digital technologies, leaving limited evidence on whether broader digital transformation is associated with stronger public health emergency management capacity at the regional level and how this relationship varies across epidemiological and innovation environments.
Methods: We analyzed a panel of 30 Chinese provinces from 2013 to 2022, comprising 300 observations. Entropy-weighted indices measured digital transformation and public health emergency management capacity. Models with province and year fixed effects and province-clustered standard errors examined the baseline association and the moderating roles of epidemic pressure and innovation capacity. Additional analyses used one-year lagged digital transformation, restricted the sample to 2018–2022, and excluded the fiscal control.
Results: Digital transformation was positively associated with public health emergency management capacity in the fully adjusted baseline model. The interaction with epidemic pressure was negative, whereas the interaction with innovation capacity was positive. The digital transformation coefficient remained positive across the additional specifications, although the lagged and 2018–2022 estimates were significant only at the 10% level.
Conclusion: Digital transformation is positively associated with public health emergency management capacity, and this association varies with epidemic pressure and innovation capacity. The findings suggest that digital public health strategies should consider epidemic demands, organizational integration, and regional innovation capabilities.

KEYWORDS
digital transformation, epidemic pressure, health system resilience, innovation capacity, public health emergency management

1 Introduction

Public health emergencies continue to expose a fundamental vulnerability in health systems: the institutions expected to respond to sudden outbreaks must simultaneously detect emerging risks, absorb surging demand, coordinate dispersed organizations, protect vulnerable populations, and maintain essential health services. The COVID-19 pandemic demonstrated that these pressures can overwhelm not only resource-constrained systems but also health systems with substantial medical infrastructure when information, workforce, supply-chain, and coordination arrangements fail to adapt at the required speed. Comparative evidence from 28 countries indicates that effective crisis responses depended on integrated governance, adequate financing, a supported workforce, access to medical technologies, timely information, and the capacity to engage communities rather than on any single preparedness resource (1). The continuing risk of emerging infectious diseases makes it urgent to identify capabilities that can be institutionalized before the next major emergency rather than improvised after disruption has already occurred.

The pandemic also revealed that apparently similar health systems can experience markedly different levels of service disruption under comparable external shocks. Evidence from ten countries found substantial variation in the maintenance of maternal, child, and other essential health services, showing that the severity of an epidemic alone does not determine health-system performance (2). What matters is whether existing resources can be rapidly reallocated, whether organizations can exchange and interpret information, and whether emergency measures can be integrated with routine healthcare delivery. Public health emergency management capacity therefore cannot be strengthened solely by expanding hospitals, personnel, or fiscal expenditure. It also requires governance arrangements that connect medical resources, administrative authority, information systems, infrastructure, and social actors. This distinction is important because many post-pandemic reforms continue to emphasize the accumulation of resources while paying less attention to how those resources are coordinated and reconfigured under uncertainty.

Recent health-system research has consequently shifted from static preparedness toward the institutional capabilities that allow systems to absorb, adapt to, and learn from disruption. However, resilience-oriented reforms face an immediate implementation problem: the capabilities highlighted after COVID-19 must be converted into routine organizational processes before political attention and emergency investment decline. A critical review of health-system resilience research warns that resilience cannot be inferred from recovery alone and must be examined through the actual capacities, distributional consequences, and institutional arrangements underlying system responses (3). This creates a pressing scientific and policy question: which system-level investments consistently strengthen public health emergency management capacity, and under what conditions do their expected benefits fail to materialize? Answering this question is necessary for distinguishing reforms that create durable emergency-management capacity from those that merely add visible infrastructure without changing how the health system operates.

Digital transformation has become one of the most prominent responses to this challenge. Governments and healthcare organizations have invested in integrated health information systems, digital surveillance, electronic records, telemedicine, mobile platforms, big-data analytics, artificial intelligence, and digitally supported administrative processes. These investments can improve the speed and reach of information exchange, connect clinical and public health data, increase the visibility of resource demand, and support coordination across organizational boundaries. Nevertheless, the expansion of digital technologies has also raised questions concerning data governance, institutional accountability, unequal access, and the distribution of technological benefits and risks. The Lancet and Financial Times Commission therefore argues that digital transformation should be governed as a structural change in health systems rather than treated as a collection of technical applications (4). From a public health emergency perspective, this means that the relevant issue is not simply whether a province possesses more digital infrastructure, but whether digital transformation improves the system's capacity to identify threats, mobilize resources, coordinate actors, and sustain emergency operations.

This distinction is particularly important because digital resources do not automatically produce stronger public health governance. Digital public health leadership requires interoperable systems, institutional authority, workforce capabilities, sustainable investment, and arrangements that connect digital information with operational decisions (5). International emergency-data projects have documented persistent obstacles involving fragmented databases, inconsistent data standards, delayed access, limited analytical capacity, and weak translation of evidence into policy (6). At the organizational level, the adoption of digital tools also depends on their alignment with strategic priorities, clinical and administrative workflows, technical architecture, implementation resources, and long-term maintenance arrangements (7). Moreover, digital applications require continuing real-world evaluation because technical validity or successful pilot implementation does not establish their effectiveness at scale (8). These findings reveal a potential capability-conversion gap: provinces may accumulate digital technologies and information resources without acquiring an equivalent capacity to use them effectively during a public health emergency.

Existing research has not adequately explained this gap. Much of the digital-health literature evaluates individual technologies, clinical applications, or organization-specific implementation projects. These studies clarify how particular tools function but provide less evidence on whether digital transformation strengthens the overall emergency management capacity of regional public health systems. More importantly, studies that report the benefits of digitalization frequently estimate average relationships without examining whether the conversion of digital resources into emergency capacity changes across operating environments. This omission is consequential because digital systems are expected to be most valuable when epidemic risks are rapidly changing, yet those same conditions generate resource scarcity, information overload, workforce pressure, and coordination congestion that may restrict their practical value. Conversely, regions with stronger innovation capacity may be better able to absorb technologies, integrate systems, solve implementation problems, and adapt digital resources to emerging needs.

China provides a valuable setting in which to examine these relationships. Provincial health systems operate within a common national institutional framework but differ considerably in digital transformation, infectious-disease exposure, medical and socioeconomic resources, infrastructure, and innovation capacity. This combination of institutional commonality and regional heterogeneity allows the study to move beyond the general question of whether digital

transformation is beneficial and address a more consequential scientific problem: Can digital transformation be converted into public health emergency management capacity under the conditions in which it is most needed, and why does this conversion vary across regions? Specifically, this study examines whether digital transformation improves public health emergency management capacity, whether epidemic pressure weakens this effect, and whether innovation capacity strengthens it. Using panel data from 30 Chinese provinces from 2013 to 2022, the study constructs entropy-weighted indices and estimates two-way fixed-effects models with interaction terms. It contributes by shifting the analytical focus from isolated digital applications to system-level capacity, identifying both a constraining and an enabling boundary condition, and providing longitudinal evidence on the uneven governance value of digital transformation. Figure 1 summarizes the research framework and empirical design of the study.

2 Theoretical framework and hypotheses

2.1 Digital transformation and public health emergency management capacity

Public health emergency management places unusually high demands on the coordination capacity of health systems. During an infectious-disease emergency, health authorities must monitor changing risks, verify epidemiological information, mobilize medical resources, coordinate government departments and healthcare providers, communicate with communities, and maintain essential services. These functions are interdependent: surveillance has limited operational value when risk information cannot guide resource allocation, while additional medical resources may remain ineffective when institutions cannot identify demand or coordinate their deployment. Recent research on essential public health functions therefore emphasizes that resilient health systems require sustained arrangements for surveillance, governance, workforce development, emergency preparedness, public communication, and multi-sectoral coordination rather than temporary interventions activated only after a crisis begins (9). Public health emergency management capacity is consequently more likely to improve when information, resources, and organizational actors can be connected through routine institutional processes.

Digital transformation can strengthen these connections by altering how information is collected, transmitted, analyzed, and incorporated into health-system decisions. Integrated electronic records, public health databases, communication networks, digital administrative platforms, and analytical technologies can reduce the separation between clinical services, disease surveillance, policy planning, and resource management. Research on national learning health and care systems shows that data-enabled infrastructure can support public health planning, integrated service delivery, real-world evidence generation, and continuous system learning when information is shared across providers and organizational levels (10). In emergency settings, these functions can shorten the interval between the emergence of a risk signal and the initiation of an administrative or clinical response. Digital transformation may thus improve public health emergency management capacity not only by increasing the quantity of available information but also by making that information more accessible and actionable across the health system.

The first mechanism concerns risk sensing and situational awareness. Infectious-disease emergencies generate rapidly changing

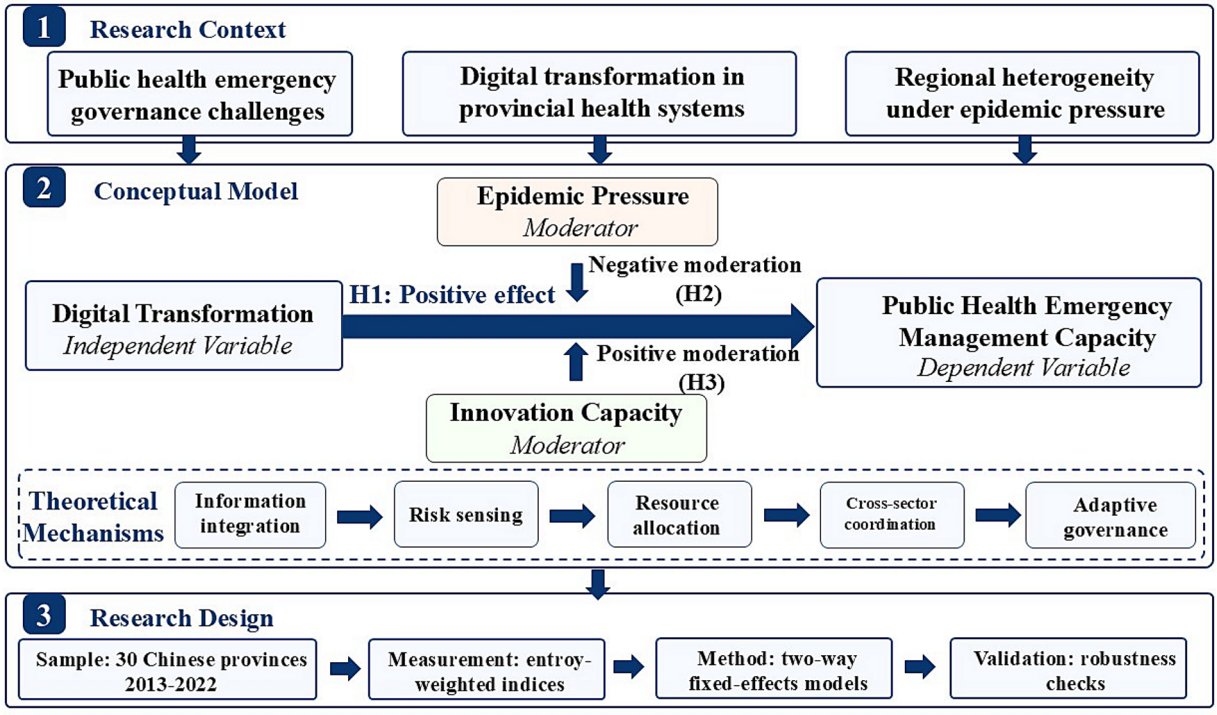

FIGURE 1
Research framework and empirical design.

information from hospitals, laboratories, disease-control agencies, communities, mobility systems, and other sources. Conventional reporting arrangements may create delays, inconsistencies, and incomplete assessments when data must pass sequentially through organizational hierarchies. Digital technologies can facilitate real-time or near-real-time reporting, combine information from multiple sources, and provide decision-makers with a more current understanding of disease patterns and service demand. An exploratory study of healthcare services found that digital technologies supported the monitoring, anticipation, response, and learning capabilities associated with organizational resilience, particularly by improving information visibility and communication during disruption (11). These capabilities can help public health agencies detect abnormal trends, identify high-risk areas, estimate demand for medical resources, and update response strategies as conditions change.

Digital transformation can also strengthen the analytical use of emergency information. Cloud computing, big-data applications, artificial intelligence, connected devices, and digital supply-chain systems can extend digitalization beyond data storage toward forecasting, operational coordination, and organizational learning. Evidence concerning Healthcare 4.0 applications during COVID-19 indicates that technologies used in supply chains, patient diagnosis, treatment, and follow-up can contribute to multiple resilience capabilities, including monitoring emerging conditions, anticipating resource requirements, responding to disruption, and learning from crisis experience (12). At the provincial level, these functions may support the integration of epidemiological trends with information on hospital capacity, personnel availability, medical supplies, and population needs. Better integration reduces the risk that departments respond to separate fragments of the same emergency without a shared operational picture.

A second mechanism is improved resource visibility and allocation. Public health emergencies frequently generate mismatches between the geographic or organizational distribution of resources and the locations in which they are urgently needed. Digital platforms can provide information on hospital beds, healthcare personnel, diagnostic facilities, medical equipment, medicines, transport capacity, and emergency supplies. By making these resources more visible, digital transformation can support transfers across institutions and administrative areas, prioritize scarce resources, and reduce duplicated or delayed allocation. However, these benefits depend on the security and reliability of the systems involved. Research on healthcare digital resilience shows that cybersecurity knowledge and security arrangements are closely connected to the absorptive, adaptive, and transformative capacities required to sustain digitalized health-system operations (13). Secure and dependable systems are especially important during emergencies because failures, cyberattacks, or inaccessible data can interrupt services at the moment when health organizations are most dependent on digital coordination.

A third mechanism concerns workforce and organizational processes. Digital transformation affects emergency capacity partly through the people and routines that convert information into action. Digital tools can support remote collaboration, standardized reporting, clinical decision support, workforce training, and communication between specialists and frontline providers. A systematic review of digital transformation in healthcare identifies workforce practices, managerial arrangements, operational efficiency, and organizational resilience as central domains through which digital technologies affect healthcare organizations (14). These workforce effects are relevant to emergency management because public health systems must rapidly expand responsibilities, redistribute personnel, and coordinate professionals who may not routinely work together.

The organizational contribution of digital transformation also extends beyond clinical processes. Emergency response depends on budgeting, procurement, logistics, human-resource management, facility operations, information administration, and interorganizational contracting. Research examining managerial support processes in healthcare organizations shows that digital technologies can reshape planning, procurement, administrative coordination, logistics, and other supporting activities, while their adoption depends on technological, organizational, and environmental conditions (15). By integrating these activities, digital transformation may reduce the separation between emergency decisions and the administrative processes required to implement them. For example, a decision to expand testing or treatment capacity is more likely to become operational when information systems connect demand estimates with procurement, personnel deployment, transportation, and financial authorization.

A fourth mechanism is cross-organizational coordination. Public health emergencies rarely remain within the boundaries of a single hospital or health department. They require vertical coordination among levels of government and horizontal coordination among public health agencies, hospitals, laboratories, universities, enterprises, community organizations, and the public. Shared digital platforms can establish common reporting interfaces, facilitate information exchange, and reduce repeated or inconsistent communication. Research on digital government transformation and emergency science communication networks further shows that technological change and coordination effectiveness depend on organizational, managerial, and institutional arrangements (16, 17). This experience illustrates how digital infrastructure can connect administrative, clinical, and logistical functions within a complex public health intervention.

Nevertheless, the presence of digital technologies does not guarantee stronger public health emergency management capacity. Digital interventions may remain disconnected from routine workflows, lack sufficient evaluation, depend on temporary project funding, or impose additional burdens on health professionals. A broad review of digital transformation research shows that implementation requires coordinated changes across organizations' core activities, supporting functions, and external ecosystems rather than the adoption of stand-alone technologies (18). This limitation is equally relevant to public health emergencies: technologies that perform successfully in pilot projects may not remain effective when applied across multiple institutions, large populations, or high-pressure operating environments.

These limitations do not negate the expected contribution of digital transformation. Rather, they indicate that its effects arise through the combination of information connectivity, resource visibility, workforce support, managerial integration, and cross-organizational coordination. Provinces with higher levels of digital transformation should be better positioned to detect risks, organize resources, connect actors, and sustain emergency operations, even though the magnitude of this contribution may depend on epidemic and regional conditions. Accordingly, the following hypothesis is proposed:

> *H1*. Digital transformation has a positive effect on public health emergency management capacity.

2.2 Epidemic pressure as a constraint on the effectiveness of digital transformation

Although digital transformation can strengthen public health emergency management capacity, its contribution depends on whether health systems can convert digital information and technological resources into coordinated action. Epidemic pressure changes the conditions under which this conversion occurs. Rapidly changing transmission patterns, uncertain clinical demand, incomplete epidemiological evidence, and fluctuating resource requirements make it more difficult for public organizations to plan and coordinate their responses. Research on digital transformation under environmental uncertainty shows that technological resources generate value only when they are combined with appropriate resource orchestration and organizational arrangements (19). Organizational resilience research similarly indicates that responding to disruption requires not only resources but also the capabilities to interpret change, adapt routines, and reconfigure operations (20). Epidemic pressure may therefore weaken the contribution of digital transformation when the rate of environmental change exceeds the health system's capacity to absorb and act on digital information.

First, epidemic pressure increases the volume, velocity, and ambiguity of information. During an unstable outbreak, health authorities may receive frequent updates from hospitals, laboratories, disease-control agencies, communities, and digital surveillance systems. Although digital platforms accelerate information transmission, they may also generate duplicated reports, conflicting indicators, repeated alerts, and interruptions to routine work. Research on the dark side of the digital workplace shows that intensive digital communication can produce information overload, technostress, and fragmented attention (21). Evidence from government communication during COVID-19 further demonstrates that response capacity depends more on the quality, timeliness, and usability of information than on its quantity; poor-quality information increases overload and weakens the ability to respond quickly (22). Consequently, the marginal benefit of digital transformation may decline when epidemic pressure makes incoming information difficult to verify, prioritize, and interpret.

Second, epidemic pressure can create resource saturation and coordination congestion. Turbulent public problems require flexible coordination, institutional adaptation, and the capacity to revise established procedures as conditions evolve (23). However, severe infectious disease pressure may simultaneously increase demand for personnel, hospital space, medical supplies, diagnostic capacity, and administrative attention. A systematic review of hospital surge capacity identifies staff, supplies, space, and organizational systems as interdependent constraints on emergency preparedness (24). Digital systems may improve the visibility of these resources, but they cannot allocate resources that are unavailable or replace the organizational authority needed to mobilize them. Moreover, research on information systems in emergency departments shows that decision-support technologies produce different effects depending on when and how information is delivered and whether it matches the cognitive requirements of decision-makers (25). Under severe epidemic pressure, additional digital inputs may therefore add complexity without resolving the underlying resource bottleneck.

Third, sustained epidemic pressure may turn digital systems from coordination instruments into additional administrative demands. Public organizations operating under pressure may have less capacity to verify data, maintain interoperability, update analytical models, or respond to repeated reporting requirements. Reviews of information overload show that excessive or poorly structured information can reduce attention, delay decisions, and increase the likelihood that important signals are overlooked (26). Effective responses require information filtering, prioritization, task redesign, role clarification, and appropriate incentive and supervision mechanisms rather than simply expanding technological capacity (27, 28). Digital transformation may remain beneficial under uncertain conditions, but its positive contribution is likely to become weaker as epidemic pressure intensifies and the public health system approaches its informational, organizational, and material limits. Accordingly, the following hypothesis is proposed:

> *H2.* Epidemic pressure negatively moderates the relationship between digital transformation and public health emergency management capacity.

2.3 Regional innovation capacity as an enabling condition

The value of digital transformation also depends on the complementary capabilities available to develop, absorb, and apply digital technologies. Digital transformation generally requires changes in organizational structures, professional competencies, operational processes, and relationships with external actors rather than the installation of technology alone. A systematic review of digital transformation research identifies organizational change and the alignment of technological and managerial elements as central to successful transformation (29). Multidisciplinary research similarly shows that digital transformation requires coordinated investments in digital resources, organizational capabilities, strategy, and ecosystem relationships (30). Innovation capacity can therefore strengthen the relationship between digital transformation and public health emergency management capacity by improving the ability of regional health systems to translate technological resources into usable governance arrangements.

First, innovation capacity facilitates technological absorption and adaptive application. Digital systems used in public health emergencies must often be modified as disease patterns, information requirements, and organizational responsibilities change. Research on artificial intelligence capability shows that technological value arises from a combination of data, technical infrastructure, human expertise, managerial coordination, and organizational resources rather than from isolated technological assets (31). Transformational leadership, organizational agility, and coherent digital strategy also help organizations adjust technologies and processes to changing operational requirements (32). In addition, configurational evidence indicates that digital transformation produces stronger innovation outcomes when combined with absorptive capacity and access to external knowledge (33). Regions with greater innovation capacity should therefore be better able to evaluate emerging technologies, integrate them with existing public health systems, and adapt them to specific emergency-management tasks.

Second, innovation capacity provides a regional ecosystem for converting knowledge into practical applications. Stronger innovation environments generally contain more skilled personnel,

research institutions, technology firms, collaborative networks, and opportunities for knowledge exchange. Evidence from small and medium-sized enterprises shows that digitalization is more likely to generate product and process innovation when organizations possess the capabilities required to use digital technologies effectively (34). Firm-level research further indicates that the innovation benefits of digital transformation are shaped by the wider regional digital industry and its knowledge spillovers (35). Absorptive capacity—including research and development, workforce training, and innovation cooperation—also mediates the relationship between digital capacity and innovation performance (36). In public health emergency management, these regional resources can support the development of surveillance tools, data-integration platforms, analytical models, cybersecurity arrangements, and digitally enabled resource-allocation systems.

Third, innovation capacity can strengthen cross-sector collaboration and continuous learning. Public health emergencies require cooperation among public agencies, hospitals, universities, research institutes, laboratories, technology firms, and community organizations. Regions with stronger innovation capacity are more likely to possess established channels through which technical knowledge, operational requirements, and feedback from users can be exchanged. These relationships can shorten the process from problem identification to technological adaptation and facilitate the revision of digital systems when initial solutions prove inadequate. Research connecting digital transformation and innovation management shows that their interaction occurs across ecosystem, organizational, and project levels, with knowledge search, recombination, and collaboration playing central roles (37). Innovation capacity should therefore make digital transformation more responsive to changing public health needs and more deeply embedded in emergency governance processes. Accordingly, the following hypothesis is proposed:

> *H3*. Innovation capacity positively moderates the relationship between digital transformation and public health emergency management capacity.

3 Materials and methods

3.1 Research design and data

This study uses a provincial-level panel dataset to examine the relationship between digital transformation and public health emergency management capacity. The unit of analysis is the province-year. The sample includes 30 provincial-level regions in China from 2013 to 2022, excluding Tibet, Hong Kong, Macao, and Taiwan due to data availability and statistical comparability. The final dataset contains 300 province-year observations.

The data were mainly collected from official statistical yearbooks, including the China Statistical Yearbook and the China Health Statistics Yearbook. These sources provide information on digital infrastructure, socioeconomic development, innovation capacity, infectious disease incidence, health resources, public expenditure, employment, and infrastructure conditions. Based on these data, this study constructs composite indices of digital transformation and public health emergency management capacity using the entropy weight method, and then estimates panel regression models to test the direct and moderating effects.

3.2 Variable measurement

The dependent variable is public health emergency management capacity, measured using an entropy-weighted composite index comprising 15 indicators across four dimensions: multi-actor coordination, medical and health support, socioeconomic stability, and infrastructure readiness. Multi-actor coordination includes social organizations, autonomous organizations, and population aging. Medical and health support includes health insurance coverage, medical and health institutions, hospital beds, health professionals, and health expenditure. Socioeconomic stability includes residents' disposable income, public budget expenditure, public budget revenue, general public service expenditure, and the urban minimum living standard. Infrastructure readiness includes road mileage and private car ownership. Population aging is negatively oriented, whereas the remaining indicators are positively oriented. Population adjustments for indicators recorded as counts or aggregate amounts are described below.

The independent variable is digital transformation, measured using an entropy-weighted composite index comprising 14 indicators across four dimensions: digital infrastructure, digital technology use, information-related knowledge resources, and digital development outcomes. The retained indicators are broadcasting coverage, television coverage, exchange capacity, long-distance optical-cable length, printed book resources, fixed telephone subscriptions, mobile telephone subscriptions, broadband Internet access, computer ownership, university students, the share of employment in the information industry, average years of schooling, R&D expenditure relative to GDP, and telecommunication business volume. A higher index score indicates a higher measured level of provincial digital transformation. Table 1 presents the revised indicator framework.

To reduce the influence of provincial population size, aggregate indicators were converted to population-adjusted measures before normalization. Optical-cable length and road mileage were expressed in kilometers per 10,000 residents; social organizations, autonomous organizations, medical institutions, and university students per 100,000 residents; and hospital beds, health professionals, and private cars per 1,000 residents. Health expenditure, public budget expenditure and revenue, and general public-service expenditure were expressed in yuan per resident. Indicators already reported as proportions or per-capita measures retained their original units. Table 1 summarizes the indicator framework.

The first moderating variable is epidemic pressure, measured as the natural logarithm of the incidence of Class A and B infectious diseases. Higher incidence reflects greater infectious-disease pressure on the provincial public health system. The second moderating variable is regional innovation capacity, measured as the natural logarithm of the number of patent authorizations. This measure captures regional innovation activity that may support the development, absorption, and application of digital technologies.

The control variables include mean years of schooling, government expenditure relative to GDP, the urban population share, and the natural logarithm of employed population. These

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TABLE 1 Measurement framework of the composite indices.

Composite index	Dimension	Main indicators	Data source
Public health emergency management capacity	Multi-actor emergency coordination	Number of social organizations; number of autonomous organizations; aging level of the population	*China Statistical Yearbook; China Health Statistics Yearbook*
	Medical and health support	Health insurance coverage; number of medical and health institutions; hospital beds; health professionals; total health expenditure	*China Statistical Yearbook; China Health Statistics Yearbook*
	Socioeconomic stability	Residents' disposable income; public budget expenditure; public budget revenue; general public service expenditure; urban minimum living standard	*China Statistical Yearbook*
	Infrastructure readiness	Road mileage; private car ownership	*China Statistical Yearbook*
Digital transformation	Information infrastructure	Broadcasting coverage; television coverage; exchange capacity; long-distance optical cable length; printed book resources	*China Statistical Yearbook*
	Information technology use	Fixed telephone ownership; mobile phone ownership; broadband Internet access; computer ownership	*China Statistical Yearbook*
	Information knowledge	University students; employment in the information industry; average years of education	*China Statistical Yearbook*
	Information effects	R&D expenditure; telecommunication business volume	*China Statistical Yearbook*

variables account for differences in educational attainment, public spending intensity, urban service conditions, and labour-force scale that may be associated with both digital transformation and public health emergency management capacity.

All variables are matched at the province-year level. The composite indices of public health emergency management capacity and digital transformation are calculated using the entropy weight method to reduce subjective weighting bias and improve comparability across provinces and years.

3.3 Construction of composite indices

Entropy weights were calculated from the pooled panel of 30 provinces observed from 2013 to 2022 ($N = 300$), not separately for each year. After the population adjustments described above, each indicator was normalized using its minimum and maximum across all 300 observations. The share of the older population was reverse-coded; all other retained indicators were positively oriented. A constant of 0.0001 was added to each normalized value before calculating its proportion within an indicator. Indicator entropy was calculated using ln(300), and the resulting information-utility values were divided by their sum to obtain weights separately for the two indices. Each province-year index score is the weighted sum of its normalized indicator values after addition of the constant. The normalization bounds and weights are therefore fixed across years.

Suppose there are n province-year observations and m indicators. The original value of indicator j for observation i is denoted as x_{ij}. Because the indicators have different units and scales, all original data are first standardized. All population adjustments were completed before min–max normalization. Each indicator was then normalized using its minimum and maximum across the pooled sample of 300 province-year observations, and entropy weights were calculated from the same pooled sample. The raw indicators entering the composite indices were not log-transformed. For positive indicators, the standardized value is calculated using Equation 1:

$$z_{ij} = \frac{x_{ij} - \min\left(x_j\right)}{\max\left(x_j\right) - \min\left(x_j\right)} \tag{1}$$

For negative indicators, the standardized value is calculated using Equation 2:

$$z_{ij} = \frac{\max\left(x_j\right) - x_{ij}}{\max\left(x_j\right) - \min\left(x_j\right)} \tag{2}$$

Where z_{ij} is the standardized value of indicator j for observation i. The direction of each indicator is determined according to its theoretical meaning. Indicators that contribute positively to digital transformation or emergency management capacity are treated as positive indicators, whereas indicators that represent pressure, vulnerability, or constraints are treated as negative indicators.

After standardization, the proportion of indicator j for observation i is calculated using Equation 3:

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}} \tag{3}$$

The entropy value of indicator j is then calculated using Equation 4:

$$e_j = -k\sum_{i=1}^{n} p_{ij} \ln\left(p_{ij}\right), k = \frac{1}{\ln\left(n\right)} \tag{4}$$

Where e_j represents the entropy value of indicator j. When p_{ij}=0, $p_{ij}\ln\left(p_{ij}\right)$ is defined as 0. The information utility value of indicator j is calculated using Equation 5:

$$d_j = 1 - e_j \tag{5}$$

The weight of indicator j is then obtained using Equation 6:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{6}$$

Finally, the composite index for each province-year observation is calculated using Equation 7:

$$Index_i = \sum_{j=1}^{m} w_j z_{ij} \tag{7}$$

Using this procedure, this study calculates two entropy-weighted composite indices: the digital transformation index and the public health emergency management capacity index. These indices are then matched with the moderating variables and control variables at the province-year level and used in the subsequent panel regression analysis.

3.4 Model specification

To examine the effect of digital transformation on public health emergency management capacity, this study estimates panel regression models with province and year fixed effects. The two-way fixed-effects specification is widely used in panel-data analysis to account simultaneously for unobserved unit-specific heterogeneity and common time-specific shocks (38, 39). Province fixed effects absorb time-invariant regional characteristics, such as geo-graphical location, historical development patterns, and institutional foundations. Year fixed effects capture nationwide policy changes, macroeconomic fluctuations, public health reforms, and other temporal shocks that affect all provinces in a given year.

First, the baseline model is specified in Equation 8:

$$PHEMC_{it} = \alpha + \beta_1 DT_{it} + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{8}$$

Where $PHEMC_{it}$ denotes public health emergency management capacity in province i in year t, and DT_{it} denotes digital transformation. $Controls_{it}$ represents a set of control variables, including education level, government intervention, urbanization level, and resident employed population. μ_i denotes province fixed effects, λ_t denotes year fixed effects, and ε_{it} is the error term. A significantly positive coefficient of β_1 would support H1.

Second, to examine the moderating role of epidemic pressure, we include digital transformation, epidemic pressure, and their interaction in the baseline specification, as shown in Equation 9:

$$PHEMC_{it} = \alpha + \beta_1 DT_{it} + \beta_2 EP_{it} + \beta_3\left(DT_{it} * EP_{it}\right) + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{9}$$

Where EP_{it} denotes epidemic pressure, measured by the incidence of Class A and B infectious diseases. The coefficient β_3 captures whether epidemic pressure changes the effect of digital transformation on public health emergency management capacity. If β_3 is significantly negative, epidemic pressure weakens the positive effect of digital transformation, supporting H2.

Third, to test the moderating role of innovation capacity, the interaction term between digital transformation and innovation capacity is added, as shown in Equation 10:

$$PHEMC_{it} = \alpha + \beta_1 DT_{it} + \beta_2 IC_{it} + \beta_3\left(DT_{it} * IC_{it}\right) + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{10}$$

Where IC_{it} denotes innovation capacity, measured by the number of patent authorizations. The coefficient β_3 captures whether innovation capacity strengthens the effect of digital transformation. If β_3 is significantly positive, innovation capacity positively moderates the relationship between digital transformation and public health emergency management capacity, supporting H3.

3.5 Analytical strategy and robustness checks

The analysis begins with descriptive statistics for the regression variables in Table 2. Table 3 then presents two baseline specifications. Model (1) reports the pooled association without control variables or fixed effects. Model (2) includes the control variables and province and year fixed effects. Table 4 examines epidemic pressure and innovation capacity in separate interaction models.

Table 5 replaces contemporaneous digital transformation with its one-year lag while retaining contemporaneous controls and province and year fixed effects. This specification examines whether prior digital transformation is associated with current emergency management capacity and reduces the estimation sample to 270 observations. Temporal ordering alone does not eliminate reverse causality or omitted-variable bias (40).

Table 6 examines sensitivity to the sample period and control-variable specification (41). Model (1) restricts the baseline analysis to 2018–2022, yielding 150 observations. Model (2) retains the full sample of 300 observations and excludes government expenditure relative to GDP while retaining mean years of schooling, the urban population share, and the logarithm of employed population. Both specifications include province and year fixed effects.

Standard errors in Tables 3–6 are clustered at the province level, with 30 clusters, allowing for heteroskedasticity and correlation of errors across years within each province. Statistical significance is assessed using two-sided tests at the 1%, 5%, and 10% levels. Province clustering does not account for residual correlation between provinces, a limitation considered when interpreting the results.

4 Results

4.1 Descriptive statistics

Table 2 summarizes the 300 province-year observations. The public health emergency management capacity index has a mean of

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TABLE 2 Descriptive statistics of variables.

Variable	Obs	Mean	Std. Dev.	Min	Max
Public health emergency management capacity	300	0.298	0.109	0.086	0.677
Digital transformation	300	0.180	0.093	0.058	0.630
Epidemic pressure	300	5.349	0.364	4.392	6.492
Innovation capacity	300	10.465	1.386	6.219	13.679
Education level	300	9.361	0.908	7.474	12.782
Government intervention	300	0.250	0.101	0.107	0.643
Urbanization level	300	0.614	0.114	0.379	0.896
Resident employed population	300	7.591	0.780	5.545	8.864

TABLE 3 Baseline regression results.

Variable	Model (1)	Model (2)
Digital transformation	0.8441*** (0.0668)	0.4377*** (0.1336)
Controls	No	Yes
Province fixed effects	No	Yes
Year fixed effects	No	Yes
Constant	0.1460*** (0.0184)	−0.6190*** (0.2341)
Adjusted R^2	0.5122	0.9686
Obs	300	300

Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 4 Moderating effects.

Variable	Model (1) Epidemic pressure	Model (2) Innovation capacity
Digital transformation	0.4260*** (0.1291)	0.3997*** (0.1304)
Epidemic pressure	0.1477*** (0.0138)	
Digital transformation* Epidemic pressure	−0.1631** (0.0606)	
Innovation capacity		0.0144* (0.0073)
Digital transformation* Innovation capacity		0.2090*** (0.0188)
Controls	Yes	Yes
Province fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Constant	−0.8167*** (0.2342)	−0.7379*** (0.1897)
Adjusted R^2	0.9685	0.9699
Obs	300	300

Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

0.298 and a standard deviation of 0.109, ranging from 0.086 to 0.677. The digital transformation index has a mean of 0.180 and a standard deviation of 0.093, with values ranging from 0.058 to 0.630. Both indices exhibit variation across the pooled provincial panel.

Epidemic pressure, measured as the natural logarithm of infectious-disease incidence, has a mean of 5.349 and a standard deviation of 0.364. Innovation capacity, measured as the natural logarithm of patent authorizations, has a mean of 10.465 and a standard deviation of 1.386.

Mean years of schooling average 9.361 years. Government expenditure relative to GDP averages 0.250, and the urban population share averages 0.614. The mean of the logarithm of employed population is 7.591.

4.2 Baseline regression results

Table 3 reports the baseline estimates. Model (1), which excludes control variables and fixed effects, shows a positive association between digital transformation and public health emergency management capacity.

Model (2) adds the control variables and province and year fixed effects. The coefficient remains positive and statistically significant at the 1% level. A 0.1-point increase in the digital transformation index is associated with an approximately 0.0438-point increase in the emergency management capacity index, conditional on the included controls and fixed effects.

These estimates are consistent with H1. The smaller coefficient in Model (2) indicates that the unadjusted association is partly accounted for by the included controls and fixed effects. The estimates do not establish a causal effect of digital transformation.

4.3 Moderating effects

Table 4 examines the two moderators in separate specifications. In Model (1), the interaction between digital transformation and epidemic pressure is negative and statistically significant at the 5% level. This result is consistent with H2, indicating that the slope relating digital transformation to emergency management capacity becomes less positive as epidemic pressure increases.

In Model (2), the interaction between digital transformation and innovation capacity is positive and statistically significant at the 1% level. This result is consistent with H3, indicating that the slope becomes more positive as innovation capacity increases.

Together, these estimates indicate that the association between digital transformation and emergency management capacity varies

TABLE 5 Lagged specification using one-period lagged digital transformation.

Variable	Model (1) Lagged specification
Lagged digital transformation	0.2852* (0.1599)
Controls	Yes
Province fixed effects	Yes
Year fixed effects	Yes
Adjusted R^2	0.9663
Obs	270

Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 6 Sensitivity analyses by sample period and fiscal control.

Variable	Model (1) 2018–2022 subsample	Model (2) No fiscal control
Digital transformation	0.3091* (0.1538)	0.3939*** (0.1399)
Province fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Adjusted R^2	0.9745	0.9680
Obs	150	300

Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

with epidemic pressure and innovation capacity. The interaction coefficients describe changes in the slope; they do not establish the statistical significance of the digital transformation association at every observed moderator value.

4.4 Lagged specification and robustness checks

Table 5 replaces contemporaneous digital transformation with its one-year lag. The lagged coefficient is positive and statistically significant at the 10% level, based on 270 observations. This estimate is consistent in direction with the baseline result, although the statistical evidence is weaker. The lagged specification examines temporal ordering but does not eliminate reverse causality or other sources of endogeneity.

Table 6 reports two additional sensitivity analyses. Model (1) restricts the sample to 2018–2022, yielding 150 observations. The digital transformation coefficient remains positive but is significant only at the 10% level. Model (2) uses the full sample of 300 observations and excludes government expenditure relative to GDP while retaining the other controls and both sets of fixed effects. The coefficient remains positive and significant at the 1% level.

The adjusted R^2 values are 0.9745 and 0.9680 for the two specifications in Table 6. These statistics describe the fit of the full specifications, including the fixed effects, and should not be interpreted as the explanatory contribution of digital transformation alone.

Overall, the positive coefficient is consistent across the baseline, lagged, and sensitivity specifications. However, the lagged and restricted-period estimates provide weaker statistical evidence than the fully adjusted baseline model.

5 Discussion

5.1 Digital transformation and the operational capacity of provincial health systems

The baseline model shows a positive association between digital transformation and public health emergency management capacity. The coefficient remains positive in the lagged and sensitivity analyses, although the lagged and 2018–2022 estimates are significant only at the 10% level. These findings indicate that digital transformation is relevant not only to the technological modernization of healthcare but also to the operational capacity of provincial health systems. Public health emergencies require health authorities to detect emerging risks, process rapidly changing information, mobilize medical and administrative resources, coordinate multiple organizations, and maintain essential services under substantial time and resource constraints. Digital transformation can support these functions by improving the speed, accessibility, and connectivity of information and by linking emergency decisions more closely with the organizational processes through which they are implemented.

The positive relationship may be explained by the ability of digital transformation to reduce fragmentation across information systems, healthcare resources, and organizational boundaries. During a public health emergency, relevant information is generated by hospitals, laboratories, disease-control agencies, government departments, communities, and other organizations. When these actors rely on separate reporting channels and administrative procedures, decision-makers may receive incomplete or delayed assessments of disease patterns, service demand, and resource availability. Digitally enabled platforms can improve the integration of epidemiological information with data on hospital beds, healthcare personnel, medical supplies, diagnostic capacity, and population needs. They can also support coordination among public health agencies, healthcare providers, universities, enterprises, communities, and social organizations. Such coordination does not require all participants to perform identical functions. Instead, digital platforms can strengthen system integration while allowing specialized organizations to retain differentiated responsibilities, consistent with network-based evidence that integration and modularization can coexist in cross-regional emergency cooperation (42). Digital transformation may therefore facilitate a shift from isolated departmental responses toward more connected and coordinated health-system operations.

These findings broaden the interpretation of digital transformation in public health emergency management. Its contribution does not arise solely from the adoption of particular technologies, such as artificial intelligence, mobile applications, big-data platforms, or online reporting systems. Rather, its practical value depends on whether technological resources are embedded in routine arrangements for information sharing, resource allocation, workforce deployment, administrative coordination, and interorganizational collaboration. Digital transformation can strengthen public health emergency management when it increases the health system's capacity

to translate risk information into timely and coordinated action. It should therefore be understood as an operational and organizational capability that connects digital infrastructure with the core functions of provincial health systems. Nevertheless, the positive average relationship does not imply that digital transformation produces uniform benefits in every region or under all crisis conditions. Its contribution remains dependent on the epidemiological and innovation environments examined in the following sections.

5.2 Boundary conditions of digital transformation

The interaction estimates indicate that the association between digital transformation and emergency management capacity varies with epidemic pressure and innovation capacity. Higher epidemic pressure is associated with a less positive slope, whereas stronger innovation capacity is associated with a more positive slope.

The negative moderating effect of epidemic pressure indicates that digital transformation may face limits under high-pressure crisis conditions. When the incidence of infectious diseases increases, public health systems must deal with rapidly growing medical demand, resource shortages, changing risk patterns, and intense administrative pressure. In such situations, digital platforms can improve information collection and communication, but they cannot fully substitute for physical resources, medical capacity, organizational readiness, or emergency coordination mechanisms. If a system is overloaded, more digital information may even increase processing pressure and coordination complexity. Therefore, digital transformation should be supported by sufficient resource reserves, emergency response protocols, and organizational coordination capacity.

The positive moderating effect of innovation capacity provides a different but complementary insight. Digital transformation requires not only infrastructure and platforms but also the ability to develop, absorb, adapt, and apply new technologies (43). Regions with stronger innovation capacity are more likely to transform digital infrastructure into practical governance tools, such as intelligent monitoring systems, data integration platforms, predictive models, and decision-support mechanisms. Innovation capacity also supports collaboration among governments, enterprises, universities, research institutions, and medical organizations, which can improve the diffusion and application of digital technologies during emergencies.

Taken together, these findings challenge a purely technology-centered view of digital transformation. Digital tools are important, but their value depends on whether the public health system has the capacity to use them under uncertainty and convert them into coordinated action. Epidemic pressure represents a constraining condition, while innovation capacity represents an enabling condition. This means that digital transformation should be understood as a conditional systemic capability embedded in a complex adaptive emergency collaboration system: it produces stronger governance effects when supported by innovation ecosystems and may produce weaker effects when the system is exposed to severe uncertainty and resource pressure (44). To synthesize the above findings, Figure 2 illustrates how digital transformation operates as a conditional systemic capability in public health emergency management.

5.3 Implications for digital public health governance

The above findings have important implications for digital public health governance. First, governments should avoid treating digital transformation as a purely technical investment. Digital platforms, data systems, and intelligent tools can improve emergency management only when they are embedded in public health emergency workflows, interdepartmental coordination mechanisms, and resource allocation processes. Therefore, the policy focus should shift from expanding digital infrastructure alone to strengthening the

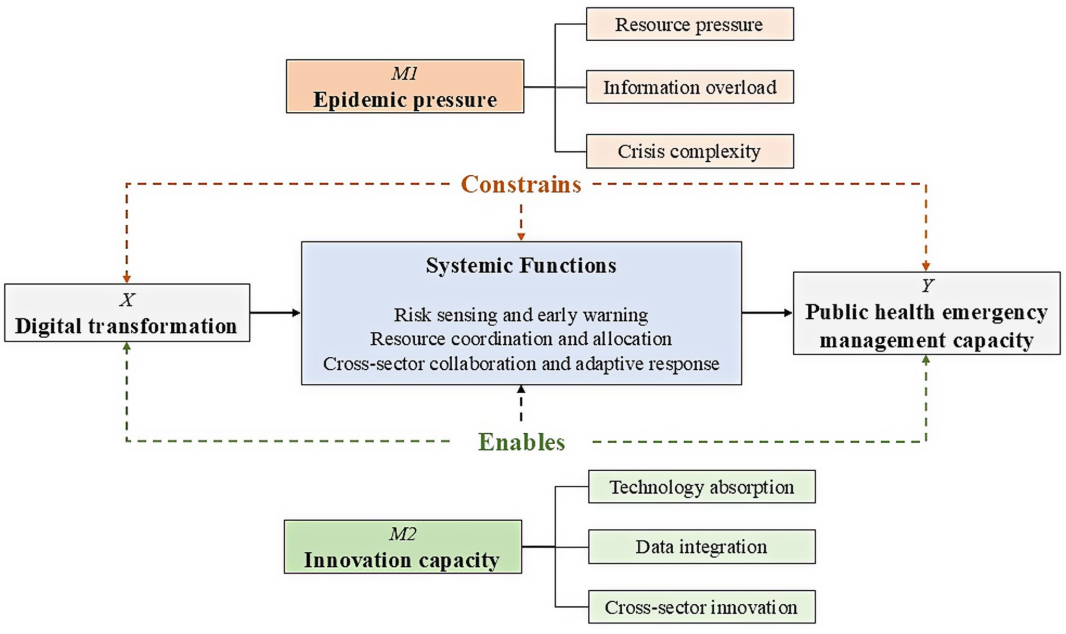

FIGURE 2
Digital transformation as a conditional systemic capability for public health emergency management.

integration between digital systems and emergency governance functions. In practice, this requires improving data interoperability, clarifying responsibilities among departments, and ensuring that digital platforms can support real-time monitoring, early warning, resource dispatching, and decision-making during public health crises.

Second, digital transformation should be accompanied by stronger uncertainty management capacity. The negative moderating effect of epidemic pressure indicates that digital tools may be constrained when public health systems face resource shortages, information overload, rapidly changing risks, and intense administrative pressure. Therefore, regions exposed to higher infectious disease risks should not rely solely on digital platforms. They also need to strengthen medical resource reserves, emergency personnel training, data verification procedures, risk communication mechanisms, and cross-departmental response protocols. Digital transformation can improve information processing and coordination, but its effectiveness depends on whether the broader emergency management system has sufficient buffering capacity to absorb shocks.

Third, innovation capacity should be treated as an enabling infrastructure for digital public health governance. The positive interaction with innovation capacity suggests that the association between digital transformation and emergency management capacity is stronger in regions with greater innovation activity. Governments should therefore promote collaboration among public agencies, medical institutions, universities, research organizations, and technology firms. Such collaboration can support the development of intelligent monitoring tools, integrated data platforms, predictive models, and decision-support systems. More importantly, innovation capacity can help transform digital infrastructure from a passive technical system into an adaptive governance capability that supports public health emergency management under complex and uncertain conditions.

The interaction results in Table 4 suggest that the association between digital transformation and public health emergency management capacity depends on the surrounding conditions. Higher epidemic pressure weakens this association, whereas stronger regional innovation capacity strengthens it. Figure 3 translates these empirical patterns into a conceptual guide for considering policy priorities. Its quadrant boundaries are illustrative; they are not estimated thresholds, and the figure does not classify the sampled provinces.

Under high epidemic pressure and limited innovation capacity, priority should be given to protecting core medical resources, simplifying digital reporting requirements, and establishing basic data interoperability. Where innovation capacity is stronger, digital systems can be used more intensively for predictive analysis, cross-organizational coordination, and adaptive resource deployment. During periods of lower epidemic pressure, regions can focus on institutionalizing digital routines, training personnel, testing interoperable platforms, and converting temporary emergency technologies into sustainable public health infrastructure. The matrix is illustrative rather than a categorical classification of the sampled provinces, but it shows how digital public health strategies can be differentiated according to the pressure and enabling conditions identified in the empirical analysis.

Beyond China, the policy matrix offers a starting point for considering how digital public health strategies can respond to epidemic pressure and draw on local innovation capacity. Its practical use will depend on how health services are organized and financed, the maturity of digital infrastructure, and the arrangements for coordination across levels of government. These institutional conditions shape how digital resources can be integrated into emergency preparedness and response.

5.4 Strengths, limitations, and future research

This study has several strengths. It shifts the analysis of digital public health from individual technologies to system-level emergency management capacity and uses longitudinal provincial data to identify

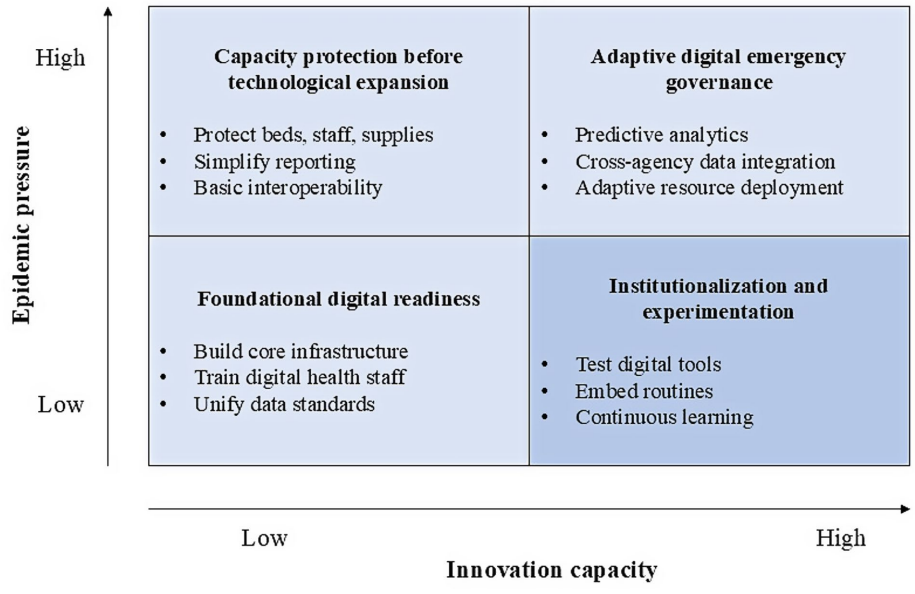

FIGURE 3
A context-sensitive policy matrix for digital public health emergency management.

both constraining and enabling conditions of digital transformation. The combination of composite-index construction, two-way fixed-effects estimation, moderation analysis, and robustness checks also provides a systematic framework for examining regional heterogeneity in digital public health governance.

Three limitations should be acknowledged. First, provincial aggregate indicators may not capture local organizational differences or actual performance during public health emergencies. Second, although fixed effects, lagged specifications, and sensitivity analyses strengthen the assessment of the association, they do not eliminate reverse causality, time-varying confounding, or measurement error; the findings therefore do not establish causality. Third, province-clustered standard errors accommodate within-province correlation over time but do not account for residual dependence across provinces, which may affect statistical inference. Future research could use more granular operational data, credible quasi-experimental designs, and diagnostics and inference methods that address cross-provincial dependence.

6 Conclusion

This study examined the relationship between digital transformation and public health emergency management capacity and assessed how this relationship varies with epidemic pressure and regional innovation capacity. Using panel data from 30 Chinese provinces from 2013 to 2022, the study constructed composite indices of digital transformation and public health emergency management capacity and estimated two-way fixed-effects models. The results show that digital transformation is significantly and positively associated with public health emergency management capacity, supporting its interpretation as a system-level capability rather than merely a collection of technological tools. The positive coefficient is consistent across the additional specifications, although the lagged and restricted-period estimates provide weaker statistical evidence.

The findings further demonstrate that the governance value of digital transformation is conditional. Epidemic pressure weakens its positive association with emergency management capacity, whereas innovation capacity strengthens it. These results suggest that digital infrastructure alone is insufficient to ensure stronger emergency management performance. Digital public health strategies should therefore combine technological investment with organizational integration, uncertainty-management capacity, interoperable data systems, and regional innovation capabilities to translate digital resources into effective emergency preparedness and response.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval were not required for this study in accordance with the local legislation and institutional requirements, as the study was based exclusively on publicly available, aggregated secondary data and did not involve human participants, individual-level data, or personally identifiable information.

Author contributions

YL: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. JC: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. LS: Formal analysis, Methodology, Resources, Software, Validation, Writing – review & editing. RC: Conceptualization, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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Conflict of interest

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