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Digital literacy's impact on digital village participation in rural left-behind women through serial mediation of political trust and self-efficacy

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Rural left-behind women, as important potential participants in Digital Village Development, face multiple challenges including limited educational resources, weak digital skills, constrained economic conditions, and traditional socio-cultural barriers. These factors severely restrict the improvement of their digital literacy and their effective participation in digital village initiatives. Drawing upon the Socio-Technical Systems (STS) theory to understand the interplay between technology and social systems, and based on the Stimulus-Organism-Response (SOR) theory to explore individual psychological processes, this study focuses on two key psychological variables—political trust and self-efficacy—to systematically explore how digital literacy influences the digital village participation of rural left-behind women through these intrinsic psychological mechanisms. The study aims to address the theoretical gaps in digital empowerment for marginalized groups and to provide solid theoretical and empirical support for promoting digital inclusion and targeted digital empowerment policies. This study utilizes field survey data from a major project funded by the National Social Science Fund of China. The sample was selected using a stratified random sampling method from several townships and villages in Shaanxi Province, yielding 1,083 valid questionnaires with an effective response rate of 91.3%. A Tobit regression model was applied to analyze the impact of digital literacy on participation in digital village initiatives. A panel conditional quantile regression was used to test the heterogeneity of this effect across different participation levels. Furthermore, a chained mediation model was employed to examine the mediating pathways of political trust and self-efficacy through which digital literacy affects digital village participation. The methodological framework is grounded in the SOR theory, providing an in-depth analysis of how digital technology stimuli influence participatory behavior through psychological states. The Tobit regression results show that digital literacy significantly enhances participation in Digital Village Development, the digital economy, and digital governance, but its effect on participation in digital benefit services is not significant. Conditional quantile regression reveals significant heterogeneity in the influence of digital literacy across different levels of participation. The chained mediation analysis indicates a significant direct effect of digital literacy (coefficient = 0.191, accounting for 60.72% of the total effect), alongside three indirect paths through political trust (17.17%), self-efficacy (16.53%), and the combined effect of political trust and self-efficacy (5.58%).These results reveal a complex multiple mediation mechanism through which digital literacy influences digital village participation among rural left-behind women. This study fills a research gap concerning the relationship between digital literacy and digital village participation among rural left-behind women and expands the application of the SOR theory in the context of Digital Village Development. The theoretical model proposed is not only suitable for the rural Chinese context but also holds universal significance for understanding digital empowerment mechanisms in marginalized populations. The findings emphasize that, beyond improving digital skills, enhancing political trust and self-efficacy is equally crucial. Accordingly, policymakers should design differentiated training and support strategies to comprehensively improve the digital literacy and participation capabilities of left-behind women, thereby facilitating the digital transformation of rural economies and societies. The sample of this study is limited to specific regions, which may affect the generalizability of the findings. The analytical models do not encompass all potential influencing

factors, and the complex role of socio-cultural contexts requires further exploration. Future research should expand the sample scope, incorporate multidimensional factors, and deepen the understanding and verification of digital empowerment mechanisms.

Keywords Rural Left-Behind women, Digital literacy, Political trust, Self-Efficacy, Digital village participation

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In the rapidly advancing digital era, the widespread adoption of information and communication technologies has emerged as a transformative force, reshaping societies and economies worldwide. While digitalization promises unprecedented opportunities for development, it also poses significant challenges, particularly for vulnerable and marginalized populations who often face a deepening digital divide[1]. This disparity in access, skills, and opportunities to effectively utilize digital technologies can exacerbate existing socio-economic inequalities, hindering inclusive growth and sustainable development, especially in rural areas[2]. Consequently, fostering digital inclusion and enhancing the digital literacy of all citizens has become a global imperative, recognized by international organizations and governments alike as fundamental to achieving comprehensive modernization.

Within this global context, China's commitment to Digital Village Development represents a pivotal national strategy to leverage informatization for agricultural and rural modernization, echoing General Secretary Xi Jinping's assertion that "without informatization, there can be no modernization; without modernization of agriculture and rural areas, there is no modernization of the entire country." This strategic initiative, deeply rooted in socio-technical systems (STS) thinking, underscores the critical need to align technological advancements with human and organizational dynamics to ensure that digital transformation truly serves the needs of rural communities[3]. Central to this endeavor is the comprehensive enhancement of rural residents' digital literacy, which is not merely about acquiring technical skills but about cultivating a core competency essential for active participation in the digital economy and governance, thereby injecting sustained momentum into rural revitalization[4]. However, despite these national efforts, significant disparities persist.This framework offers a clear explanatory path for understanding the dynamic interplay between skill acquisition, psychological empowerment, and behavioral engagement in the context of digital rural development.

Given the central role of individual capabilities in driving digital transformation, particularly within the frameworks of STS and Stimulus-Organism-Response (SOR) S-O-R, a fundamental construct for understanding rural residents' digital engagement is digital literacy. Digital literacy refers to a set of core competencies and abilities that individuals in a digital society are expected to possess throughout their learning, work, and daily life activities. It encompasses multiple dimensions, including device operation and maintenance, information acquisition and evaluation, information interaction, content creation, as well as digital risk awareness and management[5]. Specifically, device access skills involve the operation and troubleshooting of digital devices; information acquisition includes browsing, filtering, and storing information; information evaluation emphasizes critical judgment of the authenticity, authority, and quality of information; information interaction covers communication, collaboration, and dissemination via digital platforms; content creation refers to the production, editing, and reprocessing of digital content; and digital risk management focuses on risk identification, privacy protection, and the implementation of security measures. Enhancing digital literacy not only facilitates the mastery of digital technologies but also equips individuals with the capabilities necessary for active and effective participation in the digital society, thereby holding significant theoretical and practical implications.

Despite the critical importance of digital literacy for the development of digital rural areas, enhancing digital literacy among rural residents faces numerous challenges. First, the uneven distribution of educational resources and the lack of targeted digital skills training constitute structural barriers to residents' acquisition of digital competencies[6]. Second, factors such as prevailing sociocultural attitudes and varying levels of technology acceptance significantly constrain rural residents' awareness and adoption of emerging digital technologies, thereby affecting their active participation in Digital Village Development[7]. Furthermore, some rural residents may develop technophobia and resistance due to insufficient understanding of the benefits of digital technologies, which undermines their motivation and willingness to improve their digital literacy. Therefore, promoting digital literacy in rural areas requires a multidimensional approach that comprehensively addresses challenges at institutional, cultural, and cognitive levels, recognizing that it is not merely a technical fix but a complex socio-technical endeavor demanding the harmonious alignment of technological systems with human and organizational capabilities.

Existing surveys[8] indicate that the internet penetration rate and digital skills proficiency in rural areas of China are significantly lower than those in urban regions, reflecting notable deficiencies among rural residents in the application of digital technologies. This disparity, to a certain extent, limits their opportunities to participate in Digital Village Development. According to the Digital Divide Theory, unequal access to digital technologies and information exacerbates not only the urban-rural information gap but also further entrenches disparities in resource allocation and social opportunities[9]. More importantly, insufficient digital literacy may intensify information asymmetry, placing rural residents at a disadvantage in the digital economy, thereby widening the urban-rural divide. Therefore, it is imperative to systematically investigate strategies for enhancing digital literacy among rural residents, not just from a technical standpoint, but by understanding it as a holistic system that encompasses technology, people, and processes, providing theoretical support and practical guidance for bridging the digital divide and promoting comprehensive rural revitalization.

To address this challenge, China has introduced a series of policy documents aimed at enhancing digital literacy and skills among the entire population. As early as October 2021, the Central Cyberspace Affairs Commission issued the "Action Plan for Enhancing Digital Literacy and Skills Nationwide," which called for the implementation of measures to improve digital competencies across the population[10]. In December of the same year, the "14th Five-Year National Informatization Plan" was released, identifying the enhancement of digital literacy and skills as one of the ten priority actions[11]. The 20th National Congress of the Communist Party of China in 2023 further emphasized "promoting digitalization in education and building a lifelong learning society and a learning power at the national level"[12]. Additionally, the "2024 Key Tasks for Improving Digital Literacy and Skills" explicitly recognizes the raising of digital literacy as a crucial undertaking to meet the demands of the digital era, improve national quality, and promote comprehensive human development. It is also regarded as an indispensable pathway for China's transition from a major internet country to a strong cyber power, contributing to bridging the digital divide and fostering common prosperity[13].

Despite strong national emphasis and active efforts to enhance digital literacy across the population, the report titled Survey and Analysis of Digital Literacy in Rural China under the Rural Revitalization Strategy published by the Chinese Academy of Social Sciences reveals that the digital literacy level of rural residents remains relatively low. Notably, the average digital literacy score of rural villagers is significantly lower than that of urban residents by 37.5%[14]. More importantly, existing research has paid limited attention to how digital literacy influences rural residents' participation in Digital Village Development and the underlying mechanisms of this effect. To what extent does lower digital literacy constrain opportunities and equity for villagers' participation in digital rural initiatives? How does digital literacy affect villagers' psychological cognition and behaviors, thereby facilitating or hindering their engagement in Digital Village Development? These questions warrant further in-depth investigation. Therefore, this study aims to explore the impact of digital literacy on rural residents' participation in Digital Village Development and its mechanisms, with a view to providing theoretical foundations and practical guidance for improving digital literacy and promoting digital rural construction.

In the context of Digital Village Development, while enhancing the overall digital literacy of rural residents is crucial, focusing on and empowering rural left-behind women may hold greater strategic significance. Accelerated urbanization and industrialization have driven a large portion of the young labor force to cities, resulting in phenomena of rural hollowing and population left behind, with many women remaining in rural areas[15]. According to the Seventh National Population Census, there are approximately 250 million rural women in China, representing a significant human capital potential[16]. As emphasized in the Opinions on Accelerating the Revitalization of Rural Talent, priority should be given to developing rural human capital, with particular attention to nurturing local talent[17]. Furthermore, the Implementation Opinions on the "Women's Action for Rural Revitalization" clearly identify rural women not only as beneficiaries of rural revitalization but also as important agents of rural development[18]. Therefore, fully tapping into the digital literacy and skills potential of rural left-behind women is of substantial strategic importance for narrowing the urban-rural digital divide and advancing comprehensive rural revitalization.

According to the Opinions on Strengthening Care and Services for Rural Left-behind Women, rural left-behind women are defined as those whose husbands have been continuously working or doing business outside the village for more than six months, while they themselves remain living in rural areas, aged between 20 and 60 years. This official definition provides a clear target population for this study's focus on improving the digital literacy of rural left-behind women[19].

However, existing research indicates that rural left-behind women face multiple challenges in acquiring digital skills, expanding information channels, and participating socially, largely due to structural and institutional factors. On one hand, from the perspective of gender role theory, traditional gender divisions assign women primary responsibilities for household care and agricultural labor, limiting their available time and energy to engage in digital skills training[20]. On the other hand, the scarcity of educational resources and lagging digital infrastructure in rural areas restrict their access to adequate digital learning opportunities and technical support[21]. Collectively, these socio-cultural gender norms not only shape their time allocation and social roles but also exacerbate inequalities in digital skill acquisition, constituting a critical barrier to enhancing their digital literacy.

Based on the above analysis, enhancing the digital literacy of rural left-behind women and promoting their active participation in Digital Village Development holds significant theoretical and practical value. As a marginalized group within digital rural initiatives, rural left-behind women face substantial barriers to improving their digital literacy due to resource scarcity, limited social participation, and constraints imposed by traditional gender roles. Theoretically, this study contributes to broadening the research perspective at the intersection of digital literacy and rural revitalization by elucidating the mechanisms through which digital skills enhancement influences the socio-economic behaviors of left-behind women. Practically, the findings provide a scientific basis for the formulation of targeted digital empowerment policies, foster innovative models for cultivating digital capabilities among rural left-behind women, and support the implementation of rural revitalization strategies. Ultimately, this research aims to narrow the urban-rural digital divide and advance the goal of common prosperity.

With the deepening advancement of Digital Village Development, the subjectivity of rural left-behind women has gradually become more prominent, and their status in rural communication research has risen from the periphery to a central focus[22–25]. Effectively enhancing the digital literacy of rural left-behind women and promoting their active participation in digital rural construction has become an urgent issue for academic inquiry. However, existing studies have yet to adequately explore the relational mechanisms among digital literacy, political trust, and self-efficacy, leaving the dynamics through which these factors collectively influence the social participation of rural left-behind women insufficiently theorized.

A systematic review of the literature reveals that current research on Digital Village Development primarily concentrates on its theoretical connotations[26–28], salient characteristics[29,30], development level measurements[31–33], and empirical summaries[34,35]. Studies focusing on the behavioral dimensions of rural actors remain relatively limited, often centering on villagers as a whole rather than segmented groups such as village cadres[36–40], e-commerce operators[41–43], and agricultural producers[44,45]. Notably, few studies systematically investigate the unique group of rural left-behind women. As vital connectors within rural family life, rural left-behind women play a key role in linking three generations, yet their distinct needs and participation pathways in the context of digital ruralization are underexplored.Furthermore, literature on participation behaviors in digital rural areas generally acknowledges the significant impacts of participants' age[46], educational attainment, political affiliation[47], and income level[48] on their engagement levels. Nevertheless, most studies overlook the profound influence of socio-cultural environments on rural left-behind women's participation, particularly the moderating roles played by key family members such as husbands[49], elderly relatives, and children[50]. This limitation results in an incomplete understanding of the digital engagement of rural left-behind women and the challenges they face, underscoring the need to broaden research perspectives.

In political science and sociology, research on digital rural governance commonly identifies digital literacy, government trust, and self-efficacy as core endogenous variables influencing participation in digital rural initiatives. Modern political theory emphasizes that government credibility embodies the legitimacy of the state and forms the foundation of its relationship with the public. Government trust, as a critical public evaluation of the alignment between government values, decisions, and administrative actions with citizens' expectations, directly affects rural left-behind women's responsiveness to policies and willingness to engage[51]. Drawing on Trust Theory, government trust not only shapes individuals' attitudes toward the state but also reinforces their identification with and compliance to public policies.Crucially, while digital literacy empowers individuals with enhanced information access and cognitive abilities, its influence on psychological perceptions and behavioral patterns is often mediated by intrinsic belief systems. This study particularly focuses on political trust and self-efficacy as key mediating variables.Specifically, Digital literacy enhances rural left-behind women's capacity to access and comprehend government information, thereby increasing their trust in policies, improving their ability to evaluate such policies, and reducing cognitive uncertainties. This process stabilizes the coordinated relationship between the government and left-behind women, reflecting the pivotal role of information and resource acquisition in individual empowerment, as posited by Empowerment Theory. Simultaneously, self-efficacy—central to Social Cognitive Theory—determines individuals' motivation and confidence in executing tasks. Empirical evidence suggests that enhanced self-efficacy significantly boosts rural left-behind women's initiative in participating in digital rural construction, promoting a virtuous cycle between digital literacy and government trust[52].

Based on the aforementioned literature and theoretical insights, this study aims to elucidate the interaction mechanisms among digital literacy, political trust, and self-efficacy, systematically exploring their impact pathways on rural left-behind women's participation in Digital Village Development. The research intends to propose novel theoretical perspectives and practical strategies to support improvements in digital literacy and participation levels among rural left-behind women, thereby advancing the implementation of rural revitalization strategies.

To guide this investigation, the study addresses the following core research questions:

How does digital literacy influence the digital village participation behaviors of rural left-behind women?

What are the mediating mechanisms of government trust and self-efficacy in the relationship between digital literacy and digital village participation?

What are the differential manifestations of digital literacy's influence on different levels of digital village participation?

To comprehensively address these questions and ensure robust findings, this study adopts a multi-faceted empirical strategy, leveraging a suite of complementary econometric models. This approach is specifically designed to account for the unique characteristics of our participation data, explore heterogeneous effects across different levels of engagement, and meticulously delineate complex mediating mechanisms.

This research offers several significant innovations and contributions. Theoretically, it represents a pioneering effort in systematically applying an integrated framework that uniquely synthesizes the SOR theory and the STS theory to the context of digital village participation. This integration fills a crucial research gap by providing a nuanced understanding of how individual psychological processes (as explained by SOR) interact with broader technical and social structures (as conceptualized by STS) to shape digital engagement. By innovatively incorporating political trust and self-efficacy as core mediating variables within this integrated analytical framework, the study precisely reveals the complex dynamic pathways through which digital literacy influences participation. This refined theoretical model not only expands the application boundaries of SOR theory in understanding social behavior within the context of digital transformation but also offers a novel socio-technical perspective for comprehending the digital empowerment mechanisms of marginalized groups, holding significant value for comparative research and theoretical generalization.

The findings of this study will provide empirical evidence for developing more targeted digital empowerment policies, particularly in assisting rural left-behind women's digital capacity building within international development agendas. By clarifying the endogenous dynamic mechanisms of their digital village participation, this research not only contributes to the advancement of agricultural and rural modernization but also offers valuable theoretical and operational pathways for digital empowerment practices among vulnerable groups globally.

To systematically address these questions and provide a robust theoretical foundation, this study draws upon and integrates key theoretical perspectives. The subsequent section (Sect. "Theoretical framework") will elaborate on the theoretical frameworks guiding this research, laying the groundwork for our investigation.

Section "Hypotheses" will then present the detailed hypotheses derived from these frameworks. Following this, Sect. "Data sources and variable measurements" will describe the data sources, variable measurements, and the econometric models employed to rigorously test our hypotheses and investigate the complex relationships. Section "Results and discussion" will present and discuss the empirical results. Finally, Sect. "Conclusion and implications" will provide the conclusions and discuss their implications, while Sect. "Limitations and future research" will outline the study's limitations and suggest directions for future research.

Theoretical framework

Addressing a critical gap in the existing literature, which often isolates individual psychological processes from broader socio-technical contexts in digital engagement research, this study proposes a pioneering theoretical framework designed to meticulously unravel the complex, multi-layered mechanisms through which digital literacy influences rural left-behind women's participation in Digital Village Development. Our approach transcends conventional analyses by rigorously integrating two foundational theoretical perspectives: the micro-level explanatory power of the SOR theory and the macro-level contextual insights of the STS theory.

This synergistic integration not only enables a comprehensive, multi-faceted analysis but, crucially, provides a novel and robust lens to concurrently examine both the psychological underpinnings and the broader systemic forces that shape digital participation, directly underpinning the fundamental principles of our proposed chain mediation model. This model posits a sequential pathway: Digital Literacy → Political Trust → Self-Efficacy → Digital Village Participation. The theoretical foundations for each link and the overall chain are elaborated below.

Stimulus-Organism-Response theory

The SOR theory, primarily developed by Mehrabian and Russell[53], posits that an external Stimulus (S) precipitates an individual's internal Organism (O) state, which, in turn, manifests as a behavioral Response (R). This robust framework proves instrumental in dissecting the psychological and cognitive processes that translate external inputs into observable behaviors[54,55]. Within the specific context of rural digital inclusion, the SOR model provides a granular understanding of how individual predispositions and perceptions drive engagement.

In this study, digital literacy is precisely conceptualized as the primary external Stimulus (S), embodying an individual's foundational capacity to effectively engage with and navigate the digital environment. The Organism (O) encompasses the intricate internal psychological states of rural left-behind women, specifically their political trust and self-efficacy. These mediating constructs critically shape their perceptions, evaluations, and motivations concerning digital technologies and governmental initiatives related to Digital Village Development. The Response (R) is subsequently operationalized as their active participation behaviors across various facets of Digital Village Development. Consequently, the SOR framework furnishes a detailed roadmap for analyzing the sequential psychological processes that bridge digital literacy to tangible participation outcomes in this unique demographic.

Socio-Technical systems theory

Originating from the pioneering work at the Tavistock Institute in the 1950s[56], the STS theory emphasizes the inherent and inseparable interdependence between the technical subsystem (e.g., tools, processes, infrastructure, knowledge) and the social subsystem (e.g., people, roles, relationships, organizational culture). It fundamentally argues that optimal performance and sustainable development are achieved through "joint optimization," where both components are designed, developed, and managed in a mutually supportive and adaptive manner[57].

STS theory offers a critical macro-level lens for comprehending complex phenomena such as digital transformation within rural communities. It powerfully highlights that the introduction of new technologies profoundly reshapes social interactions, roles, and power dynamics, while concurrently, existing social structures and human capabilities significantly influence both the adoption and the eventual impact of technology. Applying STS theory thus underscores that sustainable digital development necessitates a meticulous consideration of how technology interfaces with human factors and social organization, decisively moving beyond a purely technological determinism to embrace a more holistic and integrated perspective[58].

Integration of theoretical perspectives

While the micro-level focus of the SOR framework offers indispensable insights into individual behavioral pathways, its explanatory power remains constrained without a robust consideration of the broader environmental context. Conversely, STS provides a crucial macro-level understanding of technology-society interactions but frequently lacks granular insight into the specific individual psychological responses and motivations. Recognizing these complementary strengths and inherent limitations, our study innovatively synthesizes the micro-level focus of the SOR theory with the macro-level insights of the STS theory, thereby constructing a profoundly holistic and explanatory framework for analyzing digital village participation among rural left-behind women. This integration allows us to capture the dynamic interplay across different analytical levels[59].

Specifically, the STS theory fundamentally enriches, contextualizes, and dynamically shapes each component of the SOR model:

Contextualizing the Stimulus (S): The availability, accessibility, and perceived usability of digital literacy-enhancing resources (e.g., tailored training programs, resilient digital infrastructure) are not merely exogenous stimuli. Instead, they are inherently and systemically shaped by the broader socio-technical system. STS enables us to comprehensively understand the systemic factors (e.g., responsive policy support, community-level technology adoption rates, the presence of social capital and networks) that critically determine the nature, efficacy, and ultimately the impact of these digital literacy stimuli.

Informing the Organism (O): The internal states of political trust and self-efficacy (Organism) are not developed in a vacuum; rather, they are deeply embedded within and influenced by the socio-technical environment. Political trust, for instance, is profoundly shaped by the perceived legitimacy, responsiveness, and fairness of the governmental social subsystem and its effective interaction with the technical subsystem (e.g., the transparency and user-friendliness of digital government platforms). Similarly, self-efficacy, while an individual psychological construct, is significantly bolstered or constrained by the perceived support from the social environment and the actual usability and reliability of the technical tools provided within the digital village ecosystem.

Framing the Response (R): Individual participation in Digital Village Development (Response) is not simply a personal, volitional choice but is powerfully influenced and bounded by the affordances and constraints intrinsic to the overall socio-technical system. The design principles of digital platforms, the nature and accessibility of digital services, prevailing social norms around technology use, and the collective benefits perceived within the community all play a decisive role in shaping, facilitating, or potentially hindering active participation.

This integrated framework, therefore, robustly posits that digital literacy and participation are not isolated individual phenomena but are profoundly embedded within, and reciprocally influenced by, the broader socio-technical fabric of the digital village. By systematically applying STS, our analysis of the SOR model rigorously considers the intricate reciprocal influences between the technical and social dimensions, leading to a significantly more nuanced and comprehensive understanding of how to genuinely foster digital empowerment and sustained participation for rural left-behind women. This holistic approach transcends simplistic deterministic views, offering a powerful and robust lens to capture the dynamic and emergent properties of human-technology interaction within a complex and evolving social setting, ultimately contributing fundamentally to the "joint optimization" of Digital Village Development. The specific mechanisms and fundamental principles of our proposed chain mediation model, directly derived from this integrative theoretical lens, are further elaborated in the following section.

Underlying mechanisms of the chain mediation model

This section further elaborates on the core mechanisms and fundamental principles that underpin our proposed serial mediation model: Digital Literacy → Political Trust → Self-Efficacy → Digital Village Participation. Drawing upon the sequential Stimulus-Organism-Response (SOR) logic and the socio-technical system (STS) dynamics, our framework posits that the entire chain is driven by two overarching principles: The Principle of Digital Governance Transparency and The Principle of Socially Reinforced Empowerment.

The Mechanism of Digital Governance Transparency (Digital Literacy → Political Trust):

Enhanced digital literacy, conceptualized as an initial stimulus (S) representing improved individual interaction with the technical subsystem, empowers rural left-behind women to more effectively access, evaluate, and comprehend governmental information through digital channels. This improved access and understanding significantly reduce information asymmetry and foster greater transparency within the broader socio-technical system, particularly regarding governance and public services (components of the social subsystem). By providing reliable and accessible information, the well-functioning technical dimension enables a more accurate and positive perception of governmental actions and intentions, which is critical for cultivating political trust (an internal organismic state, O). This principle underscores how optimizing the technical system's information delivery serves as a foundational catalyst, not merely for individual understanding, but for strengthening institutional trust and legitimacy within the social subsystem[60,61].

The Mechanism of Socially Reinforced Empowerment (Political Trust → Self-Efficacy → Digital Village Participation):

This principle articulates the subsequent sequential links: Political Trust → Self-Efficacy and Self-Efficacy → Digital Village Participation. A higher level of political trust (an organismic state, O, reflecting belief in the social subsystem's responsiveness, legitimacy, and support) creates a crucial psychological foundation. This positive expectation regarding institutional interaction subsequently leads to a significant increase in self-efficacy (another organismic state, O) among rural left-behind women. When individuals trust the system (a socio-technical environment), they perceive their participatory efforts as more likely to yield positive and secure outcomes, thereby reducing perceived risks and psychological barriers to engagement. This conducive social environment, fostered by trust, robustly encourages individuals to leverage their nascent digital capabilities, gain mastery experiences, and believe more strongly in their inherent ability to succeed. Consequently, this enhanced self-efficacy—a direct and profound result of interacting within a trusted socio-technical environment—directly translates into greater motivation, sustained effort, and perseverance in engaging with digital village initiatives (the behavioral Response, R). This principle, fully embodying the "joint optimization" spirit of STS, compellingly illuminates how a robust and trusted social environment is absolutely instrumental in fostering individual agency and strategically propelling active digital participation, demonstrating the powerful interplay between systemic trust and individual empowerment[62,63].

In sum, our multi-layered theoretical framework robustly posits that digital literacy initiates a sequential psychological process where enhanced technical competence first cultivates a positive perception of the societal environment (political trust) within the socio-technical system. This newly cultivated trust then critically bolsters individuals' belief in their own agency (self-efficacy), which ultimately drives active digital participation. This profoundly nuanced understanding provides a robust basis for explaining the dynamic interplay between individual capabilities, psychological states, and social structures in promoting digital inclusion, thereby contributing fundamentally and uniquely to the "joint optimization" of Digital Village Development and offering crucial insights for policy and practice.

This complex interplay forms the basis for the multi-layered hypotheses to be detailed in the following section.

Hypotheses

Drawing upon the integrated theoretical framework of the SOR theory and the STS theory, as discussed in Sect. 2, this section details the hypotheses exploring the complex interplay between digital literacy and rural left-behind women's participation in Digital Village Development. We conceptualize digital village initiatives as dynamic socio-technical systems, where the effectiveness of technological tools is inherently linked to the social structures and human agency, thus influencing individual psychological states and behaviors as framed by the SOR model.

Digital literacy and participation in digital village development

This study draws upon the definition of digital literacy from the "14th Five-Year Plan for National Informatization" by the Cyberspace Administration of China[64], which regards digital literacy as a comprehensive set of abilities that citizens in a digital society should possess in their learning, work, and daily lives. These abilities multidimensionally encompass the acquisition, creation, use, evaluation, interaction, sharing, innovation, protection, and ethical management of digital information. As key participants in digital rural construction, the digital literacy level of rural left-behind women directly influences their ability to effectively utilize digital technologies and integrate into and shape the modern rural socio-technical landscape.

Digital village participation is defined as a comprehensive process that involves the widespread application of digital technologies, information methods, and internet thinking to achieve modernization of rural governance, intellectualization of agricultural production, precision of rural services, and smart transformation of rural lifestyles (referencing the "China Digital Village Development Report"[65]. Specifically, it refers to the actual degree and depth of participation by rural women in digital agricultural production, digital governance collaboration, and the utilization of digital services.

Based on the SOR theoretical framework, this study views digital literacy as a crucial external stimulus (S) influencing rural women's digital village participation. Differences in digital literacy levels directly impact individuals' cognitive and emotional states (O), which in turn drive their behavioral responses (R) in digital rural-related activities.Within the broader socio-technical system of the digital village, digital literacy empowers individuals to navigate and contribute to both the technical components (e.g., using apps, accessing information) and the social components (e.g., online community engagement, understanding policy information) of this evolving environment.

Integrated with the Uses and Gratifications Theory, digital literacy not only enhances rural women's willingness to proactively utilize digital media to satisfy their information, social, and economic needs, but also boosts their motivation and depth of participation in digital rural activities. Consequently, digital literacy, as a fundamental ability and psychological cognitive condition, serves as a core driving force for promoting rural women's engagement in digital rural construction.

While acknowledging that the development of digital literacy itself is subject to various constraints in rural environments, such as lagging infrastructure investment, shortages of educational resources, traditional cultural concepts, and gender role expectations, this study focuses on exploring the theoretical mechanisms through which acquired digital literacy influences their participation behaviors. Based on the aforementioned theoretical analysis and practical context, the following hypothesis is proposed:

H1: The digital literacy of rural women is positively related to their participation in digital rural activities.

Digital literacy, political trust and participation in digital village development

China's unique social and cultural context, including its long historical traditions and cultural values, profoundly shapes public perceptions of government legitimacy and authority[66,67]. Political trust, reflecting the level of public confidence in the political system and its institutions, is widely considered a crucial psychological factor influencing citizens' policy compliance, collective action participation, and support for government decisions[68]. In the context of Digital Village Development, political trust acts as a vital bridge between the government's digital initiatives (part of the technical subsystem) and citizens' acceptance and engagement (part of the social subsystem), influencing the overall effectiveness of the socio-technical system. Amidst the accelerating digital village construction in China, particularly for rural left-behind women in transition, their level of political trust in the government not only affects their acceptance of digital-inclusive agricultural policies but is also a vital prerequisite for their active integration into and participation in digital life, enabling them to benefit from digital development dividends.

This study adopts the S-O-R theoretical framework, widely applied in psychology and behavioral research, to understand the behavioral logic of rural left-behind women within the context of digital villages. In this framework, we regard digital literacy as an external Stimulus (S), which acts upon the internal psychological state of rural left-behind women – the Organism (O), specifically, political trust. Political trust, serving as a mediating variable, further drives and influences their Response (R) in digital village construction, manifested as active participation behavior.

Political trust is not a monolithic construct but a complex concept involving multiple facets. In examining the political trust of rural left-behind women, this study rigorously follows the main dimensional division of political trust among Chinese farmers as proposed by existing research[69] and other scholars, namely: (1) Generalized Trust: primarily referring to farmers' overall evaluation and general confidence in the government as a whole and its institutions; (2) Will and Capacity: focusing on farmers' perceptions of the government's willingness and ability to solve specific problems, uphold justice for farmers, and provide effective public services. These two dimensions of trust are interrelated but distinct in their focus, jointly forming a complete picture of rural left-behind women's political trust. This study will explore the impact of digital literacy based on these two dimensions.

Specifically, enhanced digital literacy empowers rural left-behind women to more effectively access and evaluate governmental information through digital channels. This improved access reduces information asymmetry and fosters greater transparency within the socio-technical system, which is critical for cultivating political trust. For instance, by navigating official online platforms and understanding government announcements, they can form a more accurate and positive perception of government actions and intentions, thereby strengthening both their generalized trust and their perception of the government's will and capacity to serve them.

Digital literacy[70] plays a critical role in shaping the political trust of rural left-behind women, primarily influencing the dimensions of trust through the following two aspects: Firstly, enhancing digital literacy contributes to strengthening rural left-behind women's "generalized trust." Through digital channels, they can more effectively access macro information such as government policies and development goals, and utilize authoritative digital platforms to understand the overall image and performance of the government. This enhanced ability to acquire and evaluate information leads to a more accurate and balanced perception of the government as a whole and its institutions, reducing overall distrust caused by information asymmetry or bias, thereby improving generalized trust[71]. From an STS perspective, this improved information flow between the technical subsystem (digital channels) and the social subsystem (citizens' perception of government) is crucial for fostering a cohesive and trusting environment. Secondly, digital literacy also significantly impacts their perception of the government's "will and capacity." Digital literacy enables them to conveniently access and utilize digital public services closely related to their daily lives, such as online government services, legal consultation, and complaint submissions. Through these specific interactions, rural left-behind women can directly experience the efficiency, responsiveness, and problem-solving abilities of government services. Successful experiences of expressing demands through digital platforms and receiving positive feedback reinforce positive evaluations of the government's willingness and ability to solve specific problems and uphold justice. Relevant policies aimed at promoting digital inclusion in rural areas, enhancing the digitalization of public services, and encouraging grassroots governance transparency and participation provide technological support and channels, further strengthening this perception[72].These positive interactions exemplify how effective design and implementation of the technical subsystem (digital public services) can positively influence the social subsystem (citizens' trust and perception of government capability), illustrating the principle of joint optimization within the digital village.

In sum, grounded in the S-O-R theoretical framework, the external stimulus (digital literacy), by strengthening the mediating role of the organism (political trust), drives individual behavioral responses (participation in Digital Village Development).

Therefore, this study proposes the following hypothesis:

H2: Political trust mediates the relationship between digital literacy and rural left-behind women's participation in Digital Village Development.

Digital literacy, Self-Efficacy and participation in digital village development

Self-efficacy, introduced by Bandura as a core concept of social cognitive theory, refers to individuals' belief in their capability to perform specific tasks successfully. Within the context of Digital Village Development, it specifically denotes rural left-behind women's confidence in their ability to acquire and apply digital skills to participate effectively in rural development activities[73].

Using the SOR framework, digital literacy serves as the external stimulus (S) that initiates internal cognitive and affective processes within the rural women's 'organism' (O), here represented by self-efficacy—i.e., their subjective perception of digital capability and confidence. This organismic state then drives their response (R), namely, the actual participation in Digital Village Development initiatives.

The formation of self-efficacy in rural women results from interaction between digital literacy and various contextual factors. Mastery experiences gained through hands-on use of digital tools directly enhance self-efficacy by providing tangible evidence of capability. Observational learning from peers participating in digital initiatives offers vicarious reinforcement. Moreover, social environmental support, including encouragement from family, community networks, and government digital inclusion programs, acts as facilitating stimuli that strengthen belief in one's abilities. Government-engineered training and infrastructure improvements provide additional external resources that empower rural women to overcome technological barriers and thus develop higher self-efficacy[74].This interaction highlights how components of the socio-technical system—both technical resources and social support—are critical for fostering individual belief in capability, contributing to a more effective social subsystem.

Logically, digital literacy—comprising both fundamental IT operation skills and advanced information evaluation and utilization abilities—enhances rural women's self-efficacy by equipping them with the knowledge and experience to feel competent in digital tasks. As their digital literacy improves, they encounter fewer uncertainties and gain confidence, which psychologically empowers them to engage more actively in Digital Village Development behaviors such as online agricultural management, e-commerce, and participation in inclusive digital finance[75].

Therefore, self-efficacy mediates the impact of digital literacy on digital village participation by internalizing external stimuli into confident agency, consistent with the SOR model's pathway of Stimulus → Organism → Response.

Consequently, this study proposes:

H3: Self-efficacy mediates the relationship between digital literacy and rural left-behind women's participation in Digital Village Development.

Digital literacy, political trust, Self-Efficacy and participation in digital village development

This study posits a sequential mediation model wherein digital literacy (S) influences political trust, which in turn shapes self-efficacy (O), subsequently impacting participation (R) in Digital Village Development.This complex pathway unfolds within the dynamic socio-technical system of the digital village, where individual psychological states and behaviors are continually influenced by the interaction of technical tools and social structures.

Digital literacy equips rural left-behind women with crucial skills and cognitive abilities requisite for effective digital engagement[76]. As an initial stimulus (S), enhanced digital literacy is anticipated to foster positive cognitive and affective responses conducive to digital participation[77].

Within the 'organism' (O), political trust—defined as confidence in the political system and its institutions[78]—is posited as the primary mediating psychological state. Congruent with H2, digital literacy may bolster political trust by improving access to and comprehension of governmental information and by facilitating positive experiences with digital public services[79]. Elevated political trust fosters a sense of stability and perceived legitimacy concerning government-led digital initiatives.This trust, a key element of the social subsystem, is critical for the seamless operation and acceptance of the technical subsystem's offerings within the digital village.

This cultivated political trust is theorized to establish a more conducive environment for the development of self-efficacy. For rural left-behind women, trust in governmental digital initiatives can diminish perceived risks associated with new technologies[80] and augment the perceived value of participation. Such a supportive context encourages engagement in activities yielding mastery experiences and facilitates vicarious learning from peers; both are recognized as critical antecedents of self-efficacy within Social Cognitive Theory[81]. Essentially, political trust can lower psychological barriers, rendering individuals more receptive to leveraging their digital literacy and cultivating confidence in their digital capabilities.This demonstrates how a robust social subsystem, characterized by trust, can positively reinforce the individual's interaction with the technical subsystem, leading to enhanced self-efficacy.

Consequently, while digital literacy directly contributes to skill acquisition, its impact on self-efficacy is potentially amplified within a context of political trust. Heightened self-efficacy—an individual's conviction in their digital capabilities[82]—subsequently motivates more active engagement in Digital Village Development (R), such as e-commerce or online learning initiatives[83].This sequential process, where digital literacy (interaction with technology) builds trust (social acceptance) which in turn boosts self-efficacy (individual belief), culminating in participation, exemplifies the principles of joint optimization at play in creating an effective socio-technical system for rural development.

This model refines the SOR framework by delineating a sequential process within the 'organism' (O): digital literacy (S) impacts political trust, which then influences self-efficacy, ultimately triggering the behavioral response (digital village participation).

Based on this conceptualization, we propose:

H4: Political trust and subsequently self-efficacy sequentially mediate the relationship between digital literacy and rural left-behind women's participation in Digital Village Development.

Data sources and variable measurements

Data sources

The data utilized in this study were obtained from a rural field survey conducted by the research team of the National Social Science Fund Major Project titled "The Role and Function of New Media in Rural Governance under the Rural Revitalization Strategy." The survey was carried out in Shaanxi Province between July and September 2023. Drawing upon the definition of rural left-behind women provided in the "Guidelines on Strengthening Care and Services for Rural Left-Behind Women"[84], which specifies women aged between 20 and 60 who reside and live in rural areas while their husbands work or engage in business outside for more than six consecutive months, this study specifically focuses on this demographic as its research subjects. Shaanxi Province was selected based on findings from the Western Digital Economy Research Institute, which highlight that although Shaanxi's overall digital economy development level remains below the national average, its growth rate is comparatively high, ranking fifth nationwide in digital economy expansion in 2022. This distinctive profile provides a robust empirical basis for the present research.

To ensure the representativeness of the survey sample, the research team consulted with relevant experts in the field of rural revitalization and comprehensively considered various influencing factors, including regional digital economy development levels, geographical location, desired sample capacity, and sample response rates. Based on these considerations, four cities in Shaanxi Province – Xi'an, Yulin, Xianyang, and Tongchuan – were selected as the survey areas for distributing electronic questionnaires. All survey personnel were master's or doctoral candidates specializing in New Media from "Project 985" universities and had undergone professional survey training.

To ensure the statistical reliability of the research findings, the team conducted a rigorous a priori sample size calculation. Specifically, we set the significance level (α) at 0.05, statistical power ($1 - \beta$) at 0.80, and selected a medium effect size (Cohen's $d = 0.5$). Based on the sample size calculation formula, the required sample size per group was approximately 63. Considering four research variables, the recommended total sample size should be at least 252 cases. The study ultimately obtained 1083 valid samples, which not only significantly exceeded the minimum recommended sample size but also controlled the 95% confidence interval error within $\pm 3\%$, ensuring extremely high validity of the statistical conclusions.

This study employed a Stratified Multi-Stage Probability Sampling method. Through a rigorous statistical sampling procedure, system bias and random error were minimized to the greatest extent possible. The sampling process adhered to the principles of probability sampling, ensuring the randomness and representativeness of the

sample. The specific steps were as follows: First, from the four cities of Xi'an, Xianyang, Yulin, and Tongchuan, two townships were purposefully selected based on geographical location and socioeconomic characteristics, forming a stratified sampling frame. Within each township, 4–5 villages were randomly selected using Simple Random Sampling, with randomness ensured by a random number generator. In each village, 20–40 rural left-behind women were selected using Systematic Random Sampling to maximize the reduction of sampling bias.

During the survey implementation, the research team collaborated with village committees and women's federations and followed a standardized survey protocol: (1) obtaining face-to-face informed consent; (2) administration by professionally trained local interviewers; (3) providing small monetary compensation for participation; and (4) personalized follow-up for special circumstances. A total of 1186 electronic questionnaires were ultimately collected. After strict quality screening, 1083 valid questionnaires were obtained, resulting in a valid response rate of 91.3%. Criteria for excluding invalid questionnaires included: consistent selection of the same response for all items and abnormally short response time for single items (< 30 s).

The study was conducted in accordance with relevant guidelines and regulations. All participants provided informed consent prior to the study, and the research protocol received academic approval from the School of Journalism and New Media, Xi'an Jiaotong University.

Formal ethical approval from an Institutional Review Board was waived for this study. This procedure is in compliance with the 2023 revision of China's "Measures for the Ethical Review of Life Science and Medical Research Involving Humans," which exempts research from formal review if it exclusively uses fully anonymized data and poses no risk of harm to participants—conditions that this study fully meets.

Variables

Participation in digital village development

The dependent variable of this study is the digital village participation of rural left-behind women, measured based on the framework proposed in the China Digital Village Development Report[65]. This construct comprises three main dimensions that capture participants' engagement in Digital Village Development activities: digital economy, digital governance, and digital benefit services.

Digital Economy (DE): Refers to the integration of advanced information technologies—such as the Internet of Things, big data, and artificial intelligence—into rural economic activities, facilitating smart agriculture, e-commerce marketing, smart tourism, and inclusive finance.

Digital Governance (DG): Encompasses the application of digital tools to enhance data integration and sharing in village governance, including online disclosure of party affairs, village matters, financial management, e-government platforms, grid-based management, and smart emergency response systems.

Digital Benefit Services (DS): Covers digital applications aimed at improving the welfare of rural left-behind women, including "Internet + Education," "Internet + Healthcare," "Internet + Social Security," and online public legal and social assistance services.

To assess the frequency and degree of engagement in these activities, specific behavioral indicators under each dimension were evaluated using a 5-point Likert scale ranging from 1 ("Never") to 5 ("Very Often") (see Table 1 for details). The Likert scale allows for fine-grained measurement of participation intensity and reflects variability in individual engagement levels.

This measurement approach was chosen to capture the multidimensional and continuous nature of digital village participation more effectively than binary or categorical scales. The questionnaire was adapted with simplified language and practical examples appropriate to the respondents' cultural and educational context to ensure clarity and data quality.

The scale demonstrated good internal consistency, with a Cronbach's Alpha of 0.864, indicating high reliability.

Digital literacy

According to the "2023 China Rural Digital Development Research Report," as of November 2022, the number of mobile phone users in rural areas reached 290 million, with a mobile internet penetration rate of 56.9%[85]. This study measures the digital literacy level of left-behind women in rural areas based on the current status of mobile phone and internet penetration. Digital literacy is defined by referencing the "2022 National Plan for Improving National Digital Literacy and Skills" issued by the Cyberspace Administration of China, and is divided into six dimensions: Device Access (DA), Information Acquisition (IA), Information Evaluation (IE), Information Interaction (II), Content Production (CP), and Digital Risk (DR). Device Access refers to the use of smartphones as well as the ability to interconnect devices and troubleshoot faults; Information Acquisition includes skills to browse, search, and store digital information via mobile phones; Information Evaluation pertains to the ability to judge the authenticity of online information; Information Interaction involves online chatting, social interaction, and forwarding of information via mobile phones; Content Production indicates the capability to independently create and modify text, images, and videos; Digital Risk encompasses awareness of online risks and measures to protect personal information.

These six dimensions are operationalized through 14 binary-choice items (Yes = 1, No = 0), which specifically reflect the skills and behaviors across the defined dimensions.The specific items for each dimension are detailed in Table 2.To assess the internal consistency reliability of this 14-item binary scale measuring digital literacy, the Kuder-Richardson Formula 20 (KR-20) was calculated. The overall scale yielded a KR-20 coefficient of 0.88, indicating excellent internal consistency for the measure in this sample.

The reason for selecting a binary scale is as follows: the target respondents are primarily rural left-behind women, whose cultural and digital literacy levels are relatively limited. The simple Yes/No format reduces cognitive burden, avoiding possible confusion and errors caused by multi-level scales; such design simplifies the questionnaire structure, improving survey efficiency and participation rates while reducing fatigue and

Dimension	Item	Item Meaning	Mean	SD
Digital Economy (DE)	DE1Smart agriculture	Whether intelligent control is applied to the entire industrial chain of production, operation, management, and services in planting, livestock, and fisheries: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.36	1.09
	DE2 E-commerce	Whether to participate in live streaming e-commerce, community e-commerce and other promotion, selling goods, brand building, presbooking e-commerce, wholesale and other links Never used = 1; 1–2 times per week = 2; 3–5 times = 3; 1 time per day = 4; multiple per day = 5	2.67	1.12
	DE3Smart Tourism	Whether involved in smart policy-making for rural tourism, short video platform promotion of rural tourism, rural tourism financial services, and digital technology training for rural tourism talent: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.88	1.24
	DE4Digital Finance	Whether used inclusive financial services in rural areas, including payment, credit, insurance, wealth management, etc.: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.12	1.25
Digital Governance (DG)	DG1Digital Party Affairs	Whether obtained village grassroots party-building policies, publicity, party affairs transparency, and platform learning through the "Internet + Party Building" platform: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	3.12	1.15
	DG2Digital Village Affairs	Whether completed village affairs awareness, formulation and modification of villagers' self-governance regulations, and election of village committees through platforms such as WeChat and Yinnong Information Society: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.28	1.02
	DG3Digital Financial Management	Whether completed financial awareness, operation management, and decision-making services for rural contracted land, collective land, collective assets, and rural economic organizations through online platforms: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	3.02	1.06
	DG4Integrated Government Service Platform	Whether completed six types of agricultural-related government services such as social insurance, new rural cooperative medical care, labor employment, rural land transfer, homestead management, and agricultural subsidies through an integrated government service platform: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.58	1.18
	DG5Grid-based Comprehensive Governance	Whether used various specialized grid-based digital governance services such as public safety video applications, rural water level monitoring alarms, panoramic surveillance, child welfare management information systems, and anti-telecom fraud apps: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.62	1.05
	DG6Smart Emergency Management	Whether used smart emergency broadcasting, WeChat, etc., for emergency prevention, rescue, and security in case of sudden natural disasters: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.92	1.28
Digital Benefit Services (DS)	DS1Internet + education	Whether participated in online learning/training activities such as multimedia classrooms, the National Smart Education Public Service Platform, and "Double Teacher Classes" through the "Internet + Education" platform: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	3.11	1.67
	DS2The Internet + medical and health care	Whether participated in online services such as appointment registration, diagnosis, payment, and inquiry through the "Internet + Healthcare" platform: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.85	1.36
	DS3Internet + Social Security	Whether completed services such as insurance registration, social security payment and inquiry, benefit certification and receipt, employment and career training, cloud recruitment, remote interviews, and live job postings through the "Internet + Human Resources and Social Security" platform: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.81	1.39
	DS4Internet + law	Whether completed services such as legal consultation, legal aid, legal publicity, legal counsel, online case filing, online mediation, and circuit trials through the "Internet + Legal" platform: Never used = 1; 1–2 times a week = 2; 3–5 times a week = 3; Once a day = 4; Multiple times a day = 5	2.64	1.86

Table 1. Description of dependent variable items and descriptive Statistics.

omissions. Binary data also facilitates subsequent classification statistics and the application of entropy weighting methods, enhancing measurement stability and scientific rigor. Considering the rural survey environment constraints, the binary format is more suitable for paper-based or electronic questionnaires administered onsite, effectively ensuring data quality and validity.

To ensure scientific measurement, the entropy weight method was applied to normalize and weight the items in each dimension, integrating them into a composite digital literacy index that guarantees the objectivity and rationality of indicator weights. This design balances scientific rigor with the respondents' actual acceptance capabilities, improving the measurement's validity and applicability.

A pilot study involving 100 rural left-behind women was conducted to refine the digital literacy items and confirm their applicability. The pilot revealed that the proposed dimensions accurately reflected participants' digital experiences. For example, smartphone use was prevalent (around 85.5% in the pilot sample), and participants reported engaging in activities consistent with the defined dimensions, from basic information access and interaction to aspects of content creation and risk management. This feedback supported the appropriateness of the 14-item binary scale for the main study.

Control variables

According to digital divide theory, individuals with differing background characteristics exhibit significant variation in their ability to access digital resources, acquire digital skills, and engage with digital technologies in productive and daily life activities. Failure to adequately control for these background variables may compromise the validity of empirical findings[86]. Accordingly, this study recognizes the distinctive family role of rural left-behind women as the "nucleus" spanning three generations—elders, middle-aged adults, and youth—and draws on prior literature to identify ten potential factors influencing their level of participation in the digital countryside[87].

Dimension	Item	Item Meaning	Mean	SD
Device Access (DA)	DA1Device Usage	Do you currently use a smartphone? Yes = 1; No = 0	0.855	0.187
	DA2Device Interconnection	Can you choose appropriate digital tools and possible technical solutions based on actual needs to meet real-world demands, such as interconnecting smartphones with other electronic devices (e.g., screen mirroring/WeChat login on a computer)? Yes = 1; No = 0	0.558	0.287
	DA3Fault Handling	Can you solve basic problems encountered while using smartphones and other electronic devices, such as device lag, software installation/upgrade, uninstallation, etc.? Yes = 1; No = 0	0.698	0.176
Information Acquisition (IA)	IA1Information Browsing	Can you use a smartphone to browse and search for data and digital content? Yes = 1; No = 0	0.697	0.164
	IA2Information Storage	Can you extract and store information and digital content obtained from the internet? Yes = 1; No = 0	0.543	0.147
Information Evaluation (IE)	IE1 Information Identification	Can you identify the credibility of information and digital content obtained from the internet? Yes = 1; No = 0	0.846	0.287
Information Interaction (II)	II1Chat Interaction	Can you use smartphones or other electronic devices to participate in online chat interactions? Yes = 1; No = 0	0.585	0.298
	II2Information Forwarding	Can you use smartphones or other electronic devices to forward text, images, and videos to others? Yes = 1; No = 0	0.397	0.112
Content Production (CP)	CP1Content Preprocessing	Can you write text, take photos, and videos and publish them on your own? Yes = 1; No = 0	0.747	0.198
	CP2Content Reprocessing	Can you process and repost existing text, images, and videos on the internet? Yes = 1; No = 0	0.847	0.276
Digital Risk (DR)	DR1Risk Perception	Are you aware of potential security risks in the digital environment, such as online scams? Yes = 1; No = 0	0.965	0.012
	DR2Security Measures	Do you take measures to protect personal information security and privacy, such as setting a password for the device, refusing to fill in personal information when uncertain about security, and setting up payment passwords for online transactions? Yes = 1; No = 0	0.707	0.023

Table 2. Description and descriptive statistics of the independent variables.

These factors encompass individual-level characteristics, including age, educational attainment, political affiliation, and monthly income; as well as family-level characteristics, such as spouse's education level, spouse's monthly income, co-residence with children, eldest child's education level, eldest child's monthly income, and the number of elderly household members. These ten variables are incorporated as control variables in the analysis to account for confounding influences on rural left-behind women's digital village participation.

Mediating variables

This study employs political trust and self-efficacy as mediating variables influencing digital village participation among rural left-behind women. Both constructs represent subjective perceptions, necessitating precise measurement to minimize errors and ensure robust analytical results.

Political Trust(PT)was assessed using five specific indicators designed to capture multiple facets of participants' trust in local township party committees and government[78]. Three general indicators measure overall political trust and respect within the rural community: (1)The degree to which respondents believe the township party committee and government genuinely care about farmers; (2) The perceived political prestige of the township party committee and government in the rural community; (3) The respect afforded to exemplary party members and cadres affiliated with the township committee and government.

To further refine this construct, two additional indicators differentiate political trust across two critical dimensions: Desire Dimension: Whether the township party committee and government are perceived as willing to act in farmers' interests; Ability Dimension: Whether they are regarded as capable of effectively protecting and promoting farmers' interests.

The combination of these indicators provides a comprehensive evaluation of political trust, addressing both affective and competence-based components. Each item reflects a specific belief or attitude, measured to capture nuanced participant perceptions.

All items were assessed on a five-point Likert scale: 1 = Strongly Disagree/Strongly Oppose, 2 = Disagree/Oppose, 3 = Neutral, 4 = Agree/Support, and 5 = Strongly Agree/Strongly Support, with higher scores indicating greater levels of political trust. The use of a Likert-type scale allows for graded responses reflecting varying intensities of trust rather than a binary classification, enabling a more sensitive and continuous measurement of this subjective construct. The political trust scale demonstrated good internal consistency, with a Cronbach's Alpha of 0.813.

Self-Efficacy(SE)was measured using the Chinese version of the Generalized Self-Efficacy Scale (GSES) developed by Schwarzer et al.[88]. The GSES consists of ten items reflecting a unidimensional construct further categorized into two conceptual subdomains: Outcome Expectations: Beliefs regarding the likelihood of achieving desired outcomes based on one's actions; Efficacy Expectations: Confidence in one's capability to execute behaviors necessary to produce those outcomes.

Example items capture concrete tasks such as overcoming difficulties, initiating actions, and persisting despite obstacles, reflecting the individual's perceived capacity to succeed in various challenging situations relevant to rural life.

Responses to the GSES items utilize the same five-point Likert scale as described above (1 = Strongly Disagree to 5 = Strongly Agree), with higher scores indicating stronger perceived self-efficacy among respondents. The use of a Likert scale facilitates the measurement of individual differences in confidence levels along a continuous spectrum, enhancing reliability and discriminative power. The Chinese version of the GSES showed excellent reliability in this sample, with a Cronbach's Alpha of 0.875.

Additionally, special attention was given to ensure the questionnaire was clear and comprehensible to rural left-behind women respondents. The language was simplified and culturally adapted to align with their educational background and cognitive habits. Practical examples and contextual explanations accompanied key items to facilitate accurate understanding and response, thereby enhancing data quality and reliability.

Model specification

To thoroughly investigate the complex dynamics of rural left-behind women's participation in Digital Village Development, and to ensure the robustness and depth of our findings, this study employs a multi-faceted empirical strategy. This approach integrates three distinct, yet complementary, econometric models, each designed to address specific aspects of our research questions and the inherent characteristics of our data. Primarily, given the bounded and censored distribution characteristics of our dependent variable, the Tobit regression model is utilized to provide unbiased and consistent estimates of the average effects. Subsequently, to capture the heterogeneous impacts of digital literacy across different levels of participation, quantile regression is employed. Finally, to delineate the sequential psychological mechanisms through which digital literacy influences participation, a chain mediation model is constructed. This comprehensive methodological framework allows us to move beyond simple correlational analysis, offering a more nuanced and statistically rigorous understanding of digital village participation.

Tobit regression model

To accurately capture the complex dynamics of rural left-behind women's participation, and crucially, to address the bounded and censored distribution characteristics of our dependent variable, digital village participation (DV_{it}), this study constructs a panel Tobit regression model based on the baseline regression framework. This initial analysis serves a critical purpose in robustly testing our foundational hypothesis H1, which posits a direct positive relationship between digital literacy and digital village participation. By providing unbiased and consistent estimates of the effect of digital literacy on the latent propensity for participation, the Tobit model ensures that our assessment of this direct relationship is statistically sound. Furthermore, this robust estimation of the direct effect forms a crucial baseline and validation for the more complex mechanisms explored in our subsequent quantile and chain mediation models, especially as it provides the most accurate average effect of the independent variable (digital literacy) on the dependent variable (digital village participation) while correctly accounting for the data's specific distribution.

A significant proportion of our sample exhibits participation scores at the lower (1) or upper (5) bounds of the Likert scale, meaning traditional Ordinary Least Squares regression would yield biased and inconsistent estimates due to its inability to distinguish between observed boundary values and potentially more extreme underlying latent values, thus misrepresenting the true underlying relationships. The specific model is defined as:

$$DV_{it}^{*} = c_1 + \beta_1 Di_{it} + \beta_2 Pt_{it} + \beta_3 Se_{it} + \beta_4 X_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

Where:DV_{it} is digital village participation (dependent variable).Di_{it} is digital literacy (independent variable).Pt_{it} (political trust) and Se_{it} (self-efficacy) are the mediators.X_{it} represents control variables.μi denotes individual fixed effects, and ε_{it} is the random error term.c_1 is intercept.

The observed Digital Village Participation (DV_{it}) relates to the latent continuous variable (DV_{it}^{*}) as follows:

$$DV_{it} = 1 \; if \; DV_{it}* \leqslant 1; DV_{it} = DV_{it}* \; if \; 1 < DV_{it}* < 5; DV_{it} = 5 \; if \; DV_{it}* \geqslant 5 \quad (2)$$

The core advantage and necessity of the Tobit model lies in its ability to simultaneously model both the probability of participation and the intensity of participation, thereby providing unbiased and consistent estimates of the effects of independent variables on the latent (uncensored) participation level. Through maximum likelihood estimation, with the lower censoring point set at 1 and the upper censoring point set at 5, the model effectively overcomes the limitations of traditional linear regression models in handling bounded dependent variables. The model not only corrects sample selection bias but also enables accurate marginal effect estimation, providing a more precise analytical tool for in-depth analysis of the nonlinear impact of digital literacy on digital village participation.

Quantile regression model

To comprehensively reveal the multidimensional impact mechanisms of digital literacy on digital village participation, this study selects five critical quantiles (0.10, 0.25, 0.50, 0.75, and 0.90) to construct a panel conditional quantile regression(CQR) model. Compared to traditional mean regression, quantile regression can profoundly analyze the heterogeneity and asymmetry of independent variables' effects on dependent variables, exhibiting robustness to extreme values and providing a more nuanced perspective of effect analysis.

The model is specifically constructed as:

$$Q\tau\,(DV_{it}|X_{it}) = c_2 + \beta\tau_1 Di_{it} + \beta\tau_2 Pt_{it} + \beta\tau_3 Se_{it} + \beta\tau_4 X_{it} \quad (3)$$

In model (3), $Q\tau$ represents the conditional quantile at specific quantile levels. The selection of five quantiles holds significant statistical meaning: the 0.10 quantile reflects low-participation characteristics, the 0.25 quantile captures participation features in the lower quartile, the 0.50 quantile represents median-level participation, the 0.75 quantile captures participation features in the upper quartile, and the 0.90 quantile reflects high-participation characteristics.

The model estimation employs the Least Absolute Deviation estimation method, generating 95% confidence intervals through Bootstrap method (5,000 resampling iterations). The analytical strategy includes comparing coefficient differences across different quantiles, analyzing the heterogeneity of independent variables' impacts on dependent variables, and revealing potential nonlinear action mechanisms.

This multi-quantile panel data analysis approach not only enriches research methodologies but also significantly enhances the robustness and persuasiveness of research conclusions. By comprehensively portraying the multidimensional impacts of digital literacy on digital village participation and unveiling heterogeneous effects at different participation levels, this study provides deeper insights into the complex mechanisms of digital village participation, transcending the limitations of traditional mean regression.

Chain mediation model

To rigorously investigate the sequential mediating pathway through which digital literacy (Di) influences rural left-behind women's participation in Digital Village Development (Dv), this study employs Structural Equation Modeling (SEM). SEM is a powerful multivariate statistical analysis technique particularly well-suited for examining complex causal relationships, including multiple mediation effects, within a single, comprehensive statistical model. This approach offers several advantages over traditional regression-based methods for mediation analysis, such as allowing for the simultaneous estimation of all hypothesized paths, accounting for measurement error (if latent variables were used), and providing global fit indices to assess how well the entire theoretical model fits the observed data.

Based on our integrated theoretical framework, we hypothesize a sequential mediation process: Digital Literacy (Di) → Political Trust (Pt) → Self-Efficacy (Se) → Digital Village Participation (Dv). In this SEM framework, the following relationships are specified and estimated:

Path 1 (Di → Pt): The effect of digital literacy on political trust, representing the initial step in the sequential process.

Path 2 (Pt → Se): The effect of political trust on self-efficacy, indicating how the first mediator influences the second.

Path 3 (Se → Dv): The effect of self-efficacy on digital village participation, representing the final link in the chain.

Direct Path (Di → Dv): The direct effect of digital literacy on digital village participation, controlling for both political trust and self-efficacy.

Control Variables: All control variables (X_{it}) are included and regressed on Political Trust, Self-Efficacy, and Digital Village Participation in the model to account for their potential confounding effects.

The primary focus of this analysis is the sequential indirect effect of digital literacy on digital village participation, transmitted first through political trust and then through self-efficacy. This specific indirect effect is calculated as the product of the three sequential path coefficients: (Path Di→Pt) × (Path Pt→Se) × (Path Se→Dv).

The statistical significance of this sequential indirect effect, along with all direct and other indirect effects, will be assessed using bootstrapping procedures (e.g., 5,000 resamples). Bootstrapping is highly recommended for mediation analysis in SEM as it does not rely on assumptions of normality for the sampling distribution of the indirect effects.

Furthermore, to evaluate the overall tenability of the proposed sequential mediation model, various model fit indices will be examined, including but not limited to the Chi-square (χ^2) statistic, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). Given the panel nature of our data, a panel SEM approach will be employed to appropriately handle the nested data structure and within-individual variance.

This comprehensive SEM approach allows for a more granular and statistically robust understanding of the ordered psychological processes through which digital literacy's influence unfolds, providing deeper insights into the complex mechanisms of digital village participation.

Endogeneity treatment

The relationship between digital literacy and digital village participation among rural left-behind women is susceptible to endogeneity, primarily stemming from omitted variable bias and reverse causality[89], which are common challenges in observational studies. To mitigate these biases and facilitate causal inference, this study employs an instrumental variable (IV) approach, instrumenting for digital literacy using historical county-level fixed telephone line density (lines per 100 people) from a selected historical year.

The relevance of this instrument, similar to approaches in other contexts[90], stems from historical fixed-line infrastructure providing foundational exposure to communication technologies and often serving as a prerequisite for early internet access; consequently, past regional fixed-line penetration is expected to correlate positively with current digital literacy. The exclusion restriction is predicated on the argument that, conditional on a comprehensive set of contemporary control variables (including current ICT infrastructure, socioeconomic indicators, and regional fixed effects), the historical density of fixed telephone lines affects current digital village participation only through its influence on acquired digital literacy. The direct utility of this now largely superseded technology for contemporary digital village participation is negligible, and the instrument's historical nature, coupled with controls for current regional development, helps ensure it is not directly correlated with the error term in the digital village participation participation model beyond its indirect effect via digital literacy[91].

To ensure the chosen instrument is sufficiently strong and not a "weak instrument"—which could lead to biased IV estimates—its relevance will be formally tested using the first-stage F-statistic of excluded instruments. A common benchmark, such as an F-statistic value considerably greater than 10, will be used as an indicator of a strong instrument, thereby validating its use in this study[92]. This strategy aims to isolate exogenous variation in digital literacy, thereby providing more consistent estimates of its impact on digital village participation.

Results and discussion

This section presents the empirical findings derived from our multi-faceted methodological approach, designed to provide a comprehensive understanding of rural left-behind women's participation in digital village initiatives. We first address potential common method bias and confirm the reliability and validity of our measures. Subsequently, we present the baseline regression results utilizing Tobit and IV-Tobit models, which establish the average effects of digital literacy while addressing endogeneity. Following this, the heterogeneous impacts of digital literacy across different participation levels are explored through quantile regression. Finally, we delve into the underlying sequential mechanisms by presenting the results of our chain mediation analysis. This structured presentation of results aims to clearly delineate how digital literacy influences participation, the conditions under which these impacts vary, and the psychological pathways involved, thereby offering robust and nuanced evidence for our hypotheses.

Common method bias test

Common method bias (CMB) represents a critical methodological concern in social science research, as it can introduce systematic measurement errors that may distort the observed relationships between variables. To rigorously evaluate potential CMB, this study primarily employed Harman's single-factor test, a widely recognized diagnostic approach.

An exploratory factor analysis (EFA) was conducted on all key self-reported variables included in the study. The EFA revealed three factors with eigenvalues exceeding the standard cutoff of 1. Crucially, the first unrotated factor explained 34.74% of the total variance. This percentage is substantially below the conventional 50% threshold, a guideline often cited in methodological literature[93], suggesting that a single factor does not account for the majority of the covariance between the measures. Therefore, these results indicate that common method bias is unlikely to be a significant concern that would compromise the validity of our research findings. The presence of a multifactor structure further supports this, indicating substantive variance attributable to the distinct constructs rather than a single methodological artifact, thereby enhancing the credibility of our empirical analysis. Beyond this diagnostic check, proactive measures to minimize potential CMB were embedded in the study's design. Specifically, significant effort was invested in ensuring item clarity, utilizing appropriate and validated scaling techniques, and conducting thorough pilot testing to confirm respondent comprehension and the cultural appropriateness of the survey instrument for rural left-behind women.

Reliability and validity testing

This study employed SPSS 26.0 software to conduct preliminary reliability analysis and validity suitability tests on 29 measurement items across three variables: political trust (PT), self-efficacy (SE), and digital village participation (DP). The reliability analysis showed that the Cronbach's Alpha coefficients of all variables exceeded 0.7, indicating good internal consistency of the scales[94]. Regarding validity suitability, the Kaiser-Meyer-Olkin (KMO) values were all above 0.6, and Bartlett's test of sphericity was significant at the 0.01 level, confirming the appropriateness of the data for factor analysis.

Based on these results, confirmatory factor analysis was further performed using structural equation modeling software (AMOS). The measurement model demonstrated good overall fit to the data, with the following fit indices: $\chi^2/df = 2.45$, CFI = 0.95, TLI = 0.94, RMSEA = 0.058, and SRMR = 0.045[95]. Furthermore, the findings indicated that all factor loadings exceeded 0.5, demonstrating good construct validity. Composite reliability (CR) values of the latent variables were all above 0.7, and average variance extracted (AVE) values exceeded 0.5, confirming the reliability and convergent validity of the measurement model[96]. Detailed statistics are presented in Table 3.

Baseline regression: the pivotal role of digital literacy

Table 4 presents the baseline regression estimates, primarily utilizing the Tobit model to accurately capture the average impact of digital literacy on multifaceted aspects of rural left-behind women's engagement in digital village initiatives, while accounting for the censored nature of the dependent variable. To further ensure the robustness of these average effects against potential endogeneity issues, we also present results from an Instrumental

Dimension	capacity	CR	AVE	KMO	Cronbach's Alpha
Political Trust (PT)	0.824 ~0.869	0.877	0.642	0.667	0.813
Self-Efficacy (SE)	0.812 ~0.866	0.924	0.669	0.731	0.875
Digital Village Participation (DP)	0.725 ~0.874	0.918	0.738	0.732	0.864

Table 3. Reliability and validity tests. (***: $P < 0.001$).

	Digital Village Participation		Digital Economy		Digital Governance		Digital Benefit Services	
	Tobit (1)	IV-Tobit (2)	Tobit (1)	IV-Tobit (2)	Tobit (1)	IV-Tobit (2)	Tobit (1)	IV-Tobit (2)
Digital literacy	0.676*** (0.209)	0.846*** (0.211)	0.551*** (0.112)	0.610*** (0.126)	0.445** (0.165)	0.685*** (0.217)	0.167 (0.164)	0.476*** (0.174)
Political trust	0.323*** (0.109)	0.389*** (0.112)	0.402*** (0.106)	0.428*** (0.119)	0.398*** (0.109)	0.402*** (0.112)	0.443*** (0.123)	0.456*** (0.132)
Self-efficacy	0.276*** (0.006)	0.365*** (0.019)	0.025*** (0.004)	0.036*** (0.002)	0.068*** (0.017)	0.089***(0.003)	0.034 (0.029)	0.039 (0.031)
Women's age	−0.019(0.015)	−0.021(0.015)	−0.085***(0.016)	−0.089***(0.016)	−0.084***(0.018)	−0.088***(0.018)	−0.034(0.029)	−0.036(0.029)
woman political status	0.098***(0.025)	0.099***(0.025)	0.074***(0.019)	0.077***(0.019)	0.037***(0.009)	0.039***(0.009)	0.024(0.019)	0.027(0.019)
woman educational status	0.653***(0.179)	0.658***(0.179)	0.595***(0.164)	0.599***(0.164)	0.381***(0.012)	0.388***(0.012)	0.597***(0.096)	0.615***(0.096)
woman monthly income	0.046(0.039)	0.047(0.039)	0.083***(0.018)	0.088***(0.018)	0.076(0.075)	0.077(0.075)	0.064(0.058)	0.065(0.058)
Husband's Education Level	0.037***(0.009)	0.042***(0.009)	0.058***(0.016)	0.062***(0.016)	0.097***(0.029)	0.099***(0.029)	0.056***(0.018)	0.062***(0.018)
Husband monthly income	−0.058***(0.012)	−0.062***(0.012)	−0.017(0.012)	−0.018(0.012)	−0.054***(0.009)	−0.062***(0.009)	−0.023(0.019)	−0.024(0.019)
Co-residence Situation with Children	0.085***(0.029)	0.088***(0.029)	0.356(0.316)	0.362(0.316)	0.073***(0.012)	0.084***(0.012)	0.058***(0.016)	0.062***(0.016)
Eldest Child's Education Level	0.018***(0.004)	0.022***(0.004)	0.025***(0.006)	0.031***(0.006)	0.153***(0.019)	0.159***(0.019)	0.044***(0.012)	0.051***(0.012)
Eldest Child's Monthly Income	−0.047(0.039)	−0.049(0.039)	−0.053***(0.002)	−0.064***(0.002)	−0.019(0.013)	−0.020(0.013)	−0.015(0.011)	−0.016(0.011)
Number of elderly people in the family	−0.093***(0.019)	−0.098***(0.019)	−0.045***(0.008)	−0.058***(0.008)	−0.086***(0.026)	−0.092***(0.026)	−0.082(0.074)	−0.084(0.074)
Constant	0.258*** (0.065)	0.292*** (0.065)	0.498*** (0.089)	0.501*** (0.089)	0.312*** (0.074)	0.355*** (0.074)	0.621*** (0.059)	0.637*** (0.059)
LR	188.859	-	148.964	-	207.753	-	197.754	-
Wald	-	143.862	-	99.701	-	231.800	-	135.554
Log Likelihood	28.993	1976.986	36.975	1864.628	42.325	2014.824	29.385	1028.873
Pseudo R^2	−109.236	-	2.765	-	1.862	-	−1.975	-

Table 4. Benchmark regression results. Note: The values outside the brackets represent the regression coefficients, and the values inside the brackets represent the standard errors. Asterisks (*, **, *) denote statistical significance: * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Variable (IV)-Tobit model. Columns (1) and (2) detail its effect on overall digital village participation, columns (3) and (4) on digital economy involvement, columns (5) and (6) on rural digital governance participation, and columns (7) and (8) on engagement in digital benefit services.

The results consistently highlight digital literacy as a statistically significant and positive determinant of rural left-behind women's participation in digital villages, the digital economy, and digital governance across various significance levels (Table 4, columns (1), (3), (5), and (7)). While the direct effect on digital benefit services did not reach statistical significance in this baseline model (a point elaborated in Sect. 4.3.2), the overarching positive influence across other key domains is notable. Crucially, the congruence between estimates from the standard Tobit model and the IV-Tobit model—the latter specifically designed to mitigate potential endogeneity biases inherent in observational studies—lends considerable credence to the robustness of this core finding. This consistency suggests that the observed positive relationship between digital literacy and digital village participation is less likely to be an artifact of unobserved confounders or reverse causality, thereby strengthening the empirical support for Hypothesis 1: higher digital literacy is indeed associated with greater participation of rural left-behind women in digital villages.

Interpreted broadly, these findings underscore that digital literacy acts as a critical enabler. It empowers rural left-behind women, a demographic often facing unique socio-economic constraints, to more effectively integrate digital elements into agricultural production, rural governance, and daily life. This enhanced capacity to leverage digital tools and resources appears to partially offset traditional limitations related to factors such as land, capital, or information access, thereby fostering their broader engagement in the ongoing digital transformation of rural areas. This initial insight suggests that digital literacy is not merely a technical skill but a transformative capability for this specific group.

Control variables and digital participation: an overview of individual and household factors

Beyond the primary influence of digital literacy, the baseline regression models (detailed in Table 4) incorporated a suite of individual and household-level control variables to account for confounding factors. These controls provide valuable context regarding the socio-demographic and familial landscapes shaping digital engagement among rural left-behind women.

Influence of Individual Characteristics:

Consistent with established literature on the digital divide, several individual attributes demonstrated significant associations with digital participation. Educational attainment emerged as a robust positive correlate across all examined domains (digital village initiatives, digital economy, digital governance, and digital benefit services)[97]. This underscores education's foundational role in fostering cognitive skills, learning agility, and self-efficacy, which are essential for navigating and utilizing digital ecosystems. Conversely, age exhibited a significant negative correlation with participation in the digital economy and digital governance, aligning with prior research attributing this to factors such as escalating life responsibilities, traditional gender roles, and potentially lower technology acceptance among older cohorts[98]. Women's monthly income was positively associated with digital economy participation, likely reflecting increased purchasing power for digital access and enhanced economic agency[99].

Notably, political affiliation (e.g., party membership) showed a significant positive association with participation in digital village initiatives, the digital economy, and digital governance. This finding is congruent with literature suggesting that political engagement can foster a heightened sense of civic responsibility and mission, while party organizations may serve as crucial conduits for information, resources, and support related to digital projects[100]. This underscores the potential for organized political structures to act as enablers for digital inclusion within rural contexts, a pathway warranting further nuanced investigation.

Influence of Household Characteristics:

Household-level factors also played a discernible role. The educational level of husbands positively correlated with their wives' participation across all digital domains, highlighting the profound influence of spousal support, progressive gender attitudes, and potential technical guidance within the household, particularly for women whose husbands might be migrant workers[101]. Similarly, co-residence with children and the educational level of the eldest child were significantly associated with increased maternal participation in various digital spheres (digital village construction, digital governance, digital benefit services for co-residence; all domains for eldest child's education). These findings underscore the importance of intergenerational learning, the "digital feedback" effect, and the specific role of more educated children as in-house facilitators and agents of digital skill transmission[102].

Intriguingly, certain household economic indicators presented counter-intuitive relationships. The monthly income of husbands negatively correlated with wives' participation in digital village initiatives and digital governance. This divergence from assumptions of resource-driven participation may reflect complex intra-household power dynamics and the reinforcement of traditional gender roles as spousal income rises, potentially curtailing women's agency in public-sphere digital activities[103]. A similar paradoxical negative association was observed between the monthly income of the eldest child and their mothers' participation in the digital economy. This could be attributed to increased caregiving responsibilities EGFR grandmothers (the study's subjects) as their economically empowered children start their own families, thereby constraining the time and energy available for digital economic pursuits, a mechanism illuminated by theories of family economics and life-course progression[104].

Finally, the number of elderly individuals in the household demonstrated a significant negative correlation with women's participation in digital village initiatives, the digital economy, and digital governance. This aligns with time allocation theory, indicating that heightened caregiving burdens for the elderly directly impinge upon the time and resources available for other forms of engagement[105], representing a substantial structural barrier to digital inclusion for this demographic.

Specificity of factors influencing participation in digital benefit services

A notable divergence in findings emerged concerning participation in digital benefit services. Several factors that significantly influenced other digital domains—namely women's age, political affiliation, spouse's monthly income, eldest child's monthly income (for this specific service), and the number of elderly family members—were not significantly associated with engagement in these agriculturally-focused services (see Table 4, column 8).

These non-significant findings, which in some instances contrast with previous research, offer valuable insights into the specific dynamics influencing this particular form of digital engagement.The absence of an age effect, for instance, might signal a narrowing age-related digital divide specifically for accessible agricultural technologies or reflect unique characteristics of our sample[106]. Similarly, the non-significance of political affiliation suggests its established role in broader civic or community engagement may be less salient for the utilitarian adoption of specific digital agricultural tools. Regarding household economic indicators (spouse's and eldest child's income), their lack of association could imply that many digital benefit services possess relatively low entry barriers, diminishing the impact of direct economic constraints for this particular use case, or that complex intra-household resource allocations neutralize direct income effects[107]. Furthermore, the non-significant influence of the number of elderly—a factor often linked to time constraints—suggests that either the care burden's impact is less directly prohibitive for these specific, potentially more flexible, services, or its effects are counterbalanced by other unobserved household-level considerations.

These divergences underscore the highly context-dependent nature of factors influencing digital adoption, which vary considerably with the type of digital service and the specific characteristics of the target population. Future research should thus prioritize exploring the nuanced interplay of socio-cultural factors, service-specific attributes (e.g., perceived utility, ease of use, accessibility), and intra-household dynamics as potential moderators or mediators to refine theoretical models of digital agricultural service adoption.

Heterogeneity Estimation based on quantile regression

While the baseline Tobit regression provided robust estimates of the average effects of digital literacy, it is crucial to understand if and how these impacts vary across different levels of participation. To more comprehensively examine the heterogeneous effects of digital literacy on the digital village participation of rural left-behind women, this study employs a CQR model. In contrast to traditional mean regression methods that estimate average effects, CQR reveals the varying impacts of digital literacy across different quantiles of the conditional distribution of digital village participation, thereby capturing within-group heterogeneity.

Preliminary results from the Tobit regression, presented in Table 5, indicate that higher levels of digital literacy are significantly associated with increased participation in digital villages, the digital economy, and digital governance among rural left-behind women. However, no significant association was observed with participation in digital benefit services. Building upon these preliminary findings and to specifically investigate the heterogeneous associations of digital literacy across the distribution of digital village participation, we subsequently apply the CQR model to analyze its impact on participation in digital villages, the digital economy, and digital governance. The dimension of digital benefit services is excluded from this subsequent analysis due to the lack of a significant relationship in the preliminary analysis.

Quintile regression analysis of digital literacy on digital village participation

As presented in Table 5, the CQR results reveal positive estimated coefficients for digital literacy across all five examined quantiles, all of which are statistically significant at the 1% level. This indicates that higher digital literacy is significantly associated with greater participation of rural left-behind women in digital villages. Importantly, the magnitude of this association exhibits notable heterogeneity across different quantiles of the conditional distribution of participation. Specifically, the coefficient of digital literacy demonstrates an inverted U-shaped pattern, initially increasing and subsequently decreasing as the quantile rises. This suggests that digital literacy may have a stronger positive association with participation among rural left-behind women at moderate levels of involvement in digital villages compared to those with low or high participation levels. The coefficient estimate is highest at the 0.50 quantile, measuring 3.126 and statistically significant at the 1% level. Conversely, at the 0.10 quantile, the coefficient estimate is lowest at 1.132, suggesting a relatively weaker association for women with low levels of participation.

These findings, while confirming a general positive relationship between digital literacy and digital engagement, offer a more granular understanding of this association's varying strength across participation levels – a nuance often obscured by traditional mean-based analyses. Consistent with a broad body of existing research highlighting the positive role of digital skills in facilitating access to information, resources, and opportunities for participation in various digital contexts[108], our results underscore the fundamental importance of digital literacy for engaging with digital village initiatives.

However, the observed inverted U-shaped relationship provides a critical theoretical extension. For rural women at the lower end of digital village participation, the relatively smaller marginal effect of digital literacy suggests that simply possessing basic digital skills, while necessary, may not be sufficient to overcome the multifaceted barriers they face in actively engaging. These barriers could include limited digital infrastructure, lack of relevant content or services, low motivation, or absence of supporting social networks, as highlighted in later-stage Digital Divide literature and discussions around digital inclusion beyond initial access[109]. Thus, while digital literacy is beneficial, its full empowering potential might not be realized until certain threshold conditions related to motivation, access to relevant platforms, or social support are met.

Conversely, for rural women already highly engaged in digital villages (at the higher quantiles), the diminishing marginal effect of digital literacy could indicate that they have reached a point where basic digital literacy is no longer the primary bottleneck to increased participation. These individuals may have already mastered the fundamental skills required for current digital village activities. Further increases in basic digital literacy might offer limited additional benefits, as their participation levels are likely more determined by other factors such as access to advanced digital technologies or training, the quality and relevance of digital village platforms and content, opportunities for leadership or deeper involvement, or external incentives. This aligns with principles of diminishing returns to basic skills and suggests that promoting participation at higher engagement levels may require different types of interventions focused on advanced skills, platform development, or community building.

The most pronounced positive association at the middle quantiles suggests that these individuals are in a prime position to benefit significantly from improvements in digital literacy. They have likely overcome initial access barriers and possess enough basic skills to actively explore and utilize digital village resources. For this group, enhanced digital literacy directly translates into a greater ability to engage more deeply, efficiently, and

	q = 0.10	q = 0.25	q = 0.50	q = 0.75	q = 0.90
Digital literacy	2.132** (0.86)	2.265*** (0.12)	3.926*** (1.35)	4.574*** (1.33)	5.263*** (1.99)
Constant	0.661*** (0.23)	0.926** (0.37)	0.475*** (0.13)	0.417*** (0.12)	0.592*** (0.24)
R^2	0.035	0.038	0.051	0.037	0.041

Table 5. Quantile regression analysis of digital literacy on digital village participation. Note: The values outside the brackets represent the regression coefficients, and the values inside the brackets represent the standard errors. Asterisks (*, **, *) denote statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

broadly with the available digital platforms and services, maximizing their returns on digital skill investment, consistent with aspects of Human Capital Theory[110] applied to the digital domain.

In summary, our quantile regression analysis reveals a non-linear, inverted U-shaped relationship between digital literacy and participation in digital villages. While broadly consistent with prior research on the positive role of digital skills, it adds crucial nuance by showing that the empowering effect of digital literacy is strongest for those with moderate engagement levels. This highlights the need for tailored interventions: addressing foundational barriers for the least engaged, enhancing basic skills for the moderately engaged, and potentially focusing on advanced skills or platform/content development for the most engaged.

Quintile regression analysis of digital literacy on participation in digital economy

Table 6 presents the results of the quantile regression analysis, highlighting the significant heterogeneity in the impact of digital literacy on rural left-behind women's participation in the digital economy across different levels of engagement. Consistent with existing research that generally indicates a positive association between digital skills and economic participation[111], our results also demonstrate that the impact effect of digital literacy on digital economic participation is positive and statistically significant across all five quantiles (10th, 25th, 50th, 75th, and 90th percentiles).

However, importantly, as the participation quantile increases, the magnitude of the digital literacy coefficient exhibits a significant non-linear pattern, approximating a U-shaped curve. This suggests that while digital literacy is generally beneficial, its marginal effect is more pronounced among rural left-behind women with very low and very high levels of digital economic participation, compared to those with moderate participation levels. Specifically, the effect peaks at the 90th quantile, with a coefficient of 2.107 (Table 6).

These heterogeneous effects can be further understood by linking them to relevant theoretical frameworks. For rural left-behind women at lower quantiles of digital economic participation, our findings align with the principles articulated by the Capability Approach[112] and the core perspectives within the Digital Divide literature[113]. The Capability Approach theory posits that individuals require certain basic capabilities (e.g., access to resources, skills) to achieve desired socioeconomic functions (e.g., economic participation). Our finding that basic digital literacy has a strong impact at lower participation levels is consistent with this theoretical view, suggesting that digital literacy provides fundamental enabling capabilities that facilitate initial engagement with digital economic opportunities. This also dovetails with the Digital Divide literature's argument, which emphasizes the crucial role that access to and basic use of digital technologies play in bridging significant gaps in information and opportunity access for marginalized groups.

Conversely, for rural women at higher participation quantiles who are already actively utilizing digital platforms for economic independence, our findings provide empirical support for the theoretical propositions of Human Capital Theory[114] and are highly consistent with the dynamics described in the Diffusion of Innovations theory[115]. Human Capital Theory proposes that investments in skills and knowledge effectively enhance individual productivity and economic returns. Our results indicating a more significant marginal return for highly engaged individuals from higher levels of digital literacy are consistent with the view that advanced digital skills constitute valuable digital human capital, significantly aiding in optimizing existing operations and effectively expanding the scope of digital economic activities. Similarly, these women can be viewed as "early adopters" within the context of digital economic participation, for whom the gains from further digital literacy enhancement are more substantial, which validates the concept within the Diffusion of Innovations theory that early adopters are often better positioned to fully leverage new technologies.

The relatively less significant impact at the middle quantiles (q = 0.25 to q = 0.75) may represent a transitional phase where the initial digital divide effects have partially diminished, but individuals simultaneously encounter other constraints that are difficult to overcome solely through digital literacy, the importance of which then becomes more salient. Consequently, the explanation for phenomena observed in this intermediate stage may not be fully encompassed by the core tenets of the aforementioned theories and warrants further investigation in future research.

In summary, this quantile regression-based analysis offers a more refined perspective compared to traditional mean-based regression methods for understanding the mechanisms of digital literacy's impact, clearly revealing that the effect of digital literacy is not homogenous but is significantly contingent upon an individual's current level of participation in the digital economy. By integrating the empirical findings with existing theoretical frameworks, this study is able to conduct a more in-depth analysis of the underlying mechanisms behind these heterogeneous effects.

	q = 0.10	q = 0.25	q = 0.50	q = 0.75	q = 0.90
Digital literacy	1.477*** (0.03)	3.364*** (1.18)	3.154*** (1.07)	8.472*** (2.06)	6.107*** (1.55)
Constant	0.735*** (0.15)	−0.265*** (0.06)	0.436*** (0.13)	0.612*** (0.15)	0.754*** (0.27)
R^2	0.062	0.082	0.086	0.036	0.016

Table 6. Quantile regression analysis of digital literacy on digital economy participation. Note: The values outside the brackets represent the regression coefficients, and the values inside the brackets represent the standard errors. Asterisks (*, **, *) denote statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Quintile regression analysis of digital literacy on participation in digital governance

As presented in Table 7, the CQR results reveal positive and statistically significant coefficients (at the 1% level) for digital literacy across all five examined quantiles of rural left-behind women's participation in digital governance. This indicates a consistent positive impact of digital literacy on their digital governance engagement. Notably, the estimated coefficient for digital literacy exhibits a declining trend as the quantile increases. At the 0.10 quantile, the marginal effect is largest, with a coefficient of 3.025, suggesting that digital literacy improvements have the most substantial impact on rural women with low participation in digital governance.

These findings, particularly the prominent positive impact at the lower quantiles and the subsequent diminishing marginal effect, offer valuable insights when interpreted through relevant theoretical lenses and compared with existing literature. Consistent with previous research highlighting the positive association between digital skills and civic or political participation[116], our results also affirm that digital literacy is a crucial determinant of engagement in digital governance.

However, our quantile regression approach allows for a more nuanced understanding of this relationship's heterogeneity across different levels of engagement. The strong positive effect observed among rural women at the lower end of digital governance participation aligns well with the principles of the Capability Approach[117] and the core tenets of the Digital Divide literature[118]. For these individuals, who likely face significant barriers to traditional and digital civic engagement, basic digital literacy serves as a fundamental enabling capability, providing the necessary skills to access information, understand online platforms, and undertake initial participatory actions – essentially bridging a critical digital divide.

Conversely, the diminishing marginal effect of digital literacy as participation levels increase suggests that for rural women already highly engaged in digital governance, further incremental improvements in basic digital literacy yield proportionally smaller gains in participation. This pattern can be partially understood through theoretical perspectives such as the Civic Voluntarism Model[119] or by considering the concept of diminishing returns to basic skills once a certain level of proficiency and engagement is reached. Highly engaged participants may already possess sufficient basic digital literacy, and their participation levels are likely more influenced by other factors such as motivation, social networks, interest in specific governance issues, or the availability of more advanced digital skills required for deeper forms of participation. Thus, while digital literacy remains beneficial, its foundational "unlocking" power is most pronounced at the initial stages of engagement.

In summary, while confirming the widely accepted positive role of digital literacy in governance participation, our quantile regression analysis underscores the critical heterogeneity of this impact. It reveals that the empowering effect of digital literacy is most potent for those currently least engaged, highlighting its crucial role in overcoming initial barriers to participation and underscoring the need for targeted interventions focusing on basic digital skills for marginalized groups to enhance their civic engagement in the digital realm.

Robustness test

To further ensure the reliability of our research conclusions, we employed a sample size alteration method for robustness testing, with detailed results presented in Table 8. Specifically, 80% of the observations were randomly drawn from the original full sample, constituting a sub-sample of 866 units. Subsequently, this sub-sample was utilized to comprehensively re-estimate both the standard Tobit model and the IV-Tobit model (designed to address endogeneity concerns), which are central to our core analysis.

The re-estimation results clearly indicate the following:

Within the 80% sub-sample, the significant positive impacts of digital literacy on rural left-behind women's participation in overall digital village initiatives, the digital economy, and digital governance remained statistically significant, perfectly aligning with the findings from the full-sample analysis.

Similarly, the effect of digital literacy on participation in digital benefit services remained non-significant in the sub-sample, thereby corroborating the initial analytical judgment.

Crucially, a high degree of congruence with the full-sample analysis was observed in the sub-sample with respect to the direction and significance levels of the variable effects, as well as the consistency in the relationship between the estimates derived from the Tobit model and the IV-Tobit model.

These findings provide robust evidence that the primary research conclusions of this paper regarding the impact of digital literacy on rural left-behind women's participation across various dimensions of the digital village are not significantly influenced by specific sample selection and remain stable even with a reduced sample size. Therefore, the conclusions exhibit a high degree of robustness.

	q = 0.10	q = 0.25	q = 0.50	q = 0.75	q = 0.90
Digital literacy	3.025*** (0.62)	2.122*** (0.78)	1.032*** (0.26)	6.011*** (2.11)	4.221*** (1.05)
Constant	0.263*** (0.05)	1.216*** (0.46)	0.736*** (0.26)	−0.762*** (0.22)	0.754*** (0.11)
R^2	0.029	0.012	0.047	0.063	0.027

Table 7. Quantile regression analysis of digital literacy on digital governance participation. Note: The values outside the brackets represent the regression coefficients, and the values inside the brackets represent the standard errors. Asterisks (*, **, *) denote statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

	Digital Village Participation		Digital Economy		Digital Governance		Digital Benefit Services	
	Tobit (1)	IV-Tobit (2)	Tobit (1)	IV-Tobit (2)	Tobit (1)	IV-Tobit (2)	Tobit (1)	IV-Tobit (2)
Digital literacy	0.565*** (0.116)	0.645*** (0.175)	0.354*** (0.057)	0.368*** (0.155)	0.024*** (0.002)	0.175*** (0.016)	0.265 (0.156)	0.369*** (0.068)
Political trust	0.324*** (0.123)	0.388***(0.074)	0.365*** (0.016)	0.424*** (0.135)	0.365*** (0.107)	0.416*** (0.167)	0.399*** (0.176)	0.443*** (0.177)
Self-efficacy	0.315*** (0.121)	0.397*** (0.116)	0.372** (0.176)	0.416** (0.198)	0.287*** (0.064)	0.375*** (0.098)	0.376 (0.354)	0.466* (0.276)
Women's age	−0.054**(0.023)	−0.058**(0.021)	−0.082***(0.006)	−0.087***(0.009)	−0.038***(0.015)	−0.041***(0.012)	−0.073(0.063)	−0.075(0.066)
woman political status	0.018***(0.005)	0.028***(0.008)	0.024***(0.003)	0.028***(0.006)	0.172***(0.035)	0.178***(0.036)	0.083***(0.029)	0.088***(0.022)
woman educational status	0.067***(0.014)	0.069***(0.012)	0.065***(0.010)	0.068***(0.012)	0.026***(0.006)	0.032***(0.007)	0.037(0.028)	0.039(0.021)
woman monthly income	0.046(0.029)	0.047(0.031)	0.083***(0.018)	0.088***(0.012)	0.118***(0.012)	0.124***(0.009)	1.174***(0.058)	1.179***(0.051)
Husband's Education Level	0.018***(0.001)	0.022***(0.005)	0.045***(0.016)	0.053***(0.013)	0.028***(0.006)	0.031***(0.008)	0.043(0.036)	0.044(0.035)
Husband monthly income	−0.071***(0.019)	−0.077***(0.020)	−0.028(0.025)	−0.029(0.021)	−0.048***(0.014)	−0.052***(0.009)	−0.073(0.057)	−0.075(0.053)
Co-residence Situation with Children	0.078***(0.019)	0.082***(0.014)	0.052***(0.016)	0.058***(0.013)	0.038***(0.004)	0.041***(0.006)	0.041***(0.016)	0.045***(0.013)
Eldest Child's Education Level	0.048***(0.014)	0.052***(0.009)	0.018***(0.006)	0.023***(0.007)	0.076***(0.006)	0.079***(0.012)	0.034***(0.003)	0.036***(0.005)
Eldest Child's Monthly Income	−0.045(0.032)	−0.047(0.026)	−0.058***(0.012)	−0.061***(0.018)	−0.027***(0.003)	−0.034***(0.009)	−0.037***(0.014)	−0.039***(0.012)
Number of elderly people in the family	−0.065***(0.013)	−0.072***(0.011)	−0.015***(0.004)	−0.021***(0.006)	−0.037***(0.006)	−0.041***(0.011)	−0.019(0.012)	−0.019(0.012)
Constant	1.067*** (0.058)	2.247*** (0.052)	2.618*** (0.086)	1.397*** (0.088)	3.317*** (0.073)	2.528*** (0.053)	2.619*** (0.078)	1.598*** (0.078)
LR	135.546	-	167.658	-	165.323	-	186.534	-
Wald	-	145.768	-	161.645	-	74.747	-	156.638
Log Likelihood	54.547	1756.365	52.9236	1568.549	37.457	2354.472	47.756	1546.628
Pseudo R^2	5.525	-	1.636	-	0.352	-	1.653	-

Table 8. Regression results of 80% of sample data. Note: The values outside the brackets represent the regression coefficients, and the values inside the brackets represent the standard errors. Asterisks (*, **, *) denote statistical significance: * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Chain mediation effect test

Having established the average effects and explored the heterogeneous impacts of digital literacy, this section delves into the underlying psychological mechanisms through which digital literacy influences digital village participation. To examine the direct and indirect effects, and specifically to test our hypothesized sequential mediating pathway (Di → Pt → Se → Dv), we employed Structural Equation Modeling (SEM). SEM offers a robust and flexible framework for simultaneously estimating multiple regression equations, assessing complex direct and indirect relationships, and evaluating the overall fit of the theoretical model to the observed data.

The analysis was conducted using AMOS 28.0 software. We specified a fully recursive structural model, as illustrated in Fig. 1, with digital literacy (Di) as the exogenous predictor, political trust (Pt) and self-efficacy (Se) as sequential mediators, and digital village participation (Dv) as the endogenous outcome. The maximum likelihood estimation method was utilized, and the robustness of the standard errors and confidence intervals for indirect effects was assessed using the bootstrap method with 5,000 resamples.

Model Fit Assessment:

Prior to interpreting the path coefficients, the overall fit of the hypothesized model was evaluated using a range of standard fit indices. The results indicated a good fit of the model to the observed data: $\chi^2/df = 2.85$, CFI = 0.95, TLI = 0.94, RMSEA = 0.062(95% CI = [0.058–0.065]), and SRMR = 0.048. These values generally meet the commonly accepted criteria for good model fit, suggesting that our hypothesized theoretical model adequately represents the relationships among the constructs.

Direct and Indirect Effects Analysis:

As presented in Table 9; Fig. 1, the analysis revealed a significant direct effect of digital literacy on the digital village participation of rural left-behind women (Di → Dv). The estimated standardized direct path coefficient was 0.191 ($p<0.001$), indicating statistical significance. This finding provides support for Hypothesis 1, suggesting that digital literacy directly contributes to participation, independent of the proposed mediators. This direct effect accounted for approximately 60.72% (0.191/0.315) of the total observed effect, calculated based on standardized effects.

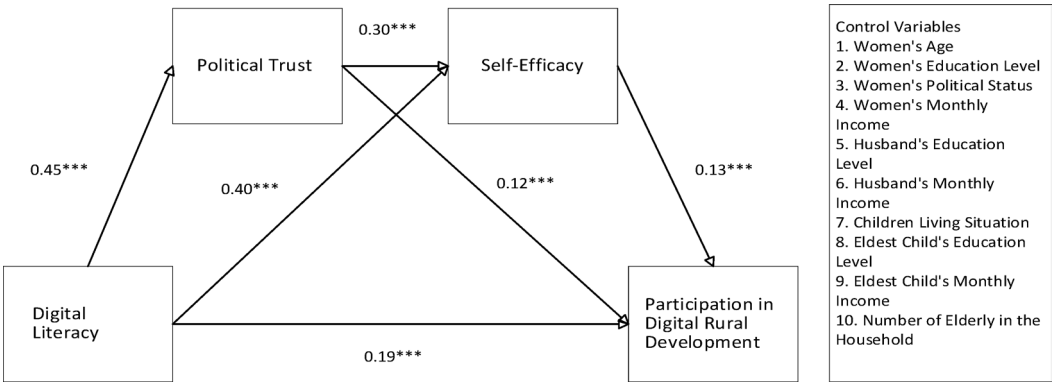

Fig. 1. Structural Model Path Coefficient Diagram.

Effect type	Effect type	Effect value	95% Confidence Interval		Mediating Effect	Effect Size
			Lower Bound	Upper Bound		
Direct Effect	Digital Village Participation ← Digital Literacy	0.191	0.065	0.278	Test passed	60.72%
Indirect Effect	Digital Village Participation ← Political Trust ← Digital Literacy	0.054	0.023	0.070	Test passed	17.17%
	Digital Village Participation ← Self-efficacy ← Digital Literacy	0.052	0.026	0.073	Test passed	16.53%
	Digital Village Participation ← Self-efficacy ← Political Trust ← Digital Literacy	0.018	0.005	0.023	Test passed	5.58%
Total Mediating Effect		0.124	0.081	0.138		39.28%
Total Effect		0.315	0.170	0.416		100.00%

Table 9. Mediation effect test and effect quantity.

Furthermore, the analysis indicated a significant total indirect effect of digital literacy on digital village participation through the combined influence of political trust and self-efficacy. The estimated standardized total indirect effect was 0.124 (95% CI = 0.081, 0.138), with the confidence interval not including zero, signifying the presence of significant mediation. This total indirect effect accounted for approximately 39.28% (0.124/0.315) of the total effect of digital literacy on participation, calculated based on standardized effects. Given that both the direct effect and the total indirect effect are statistically significant, these findings collectively indicate that political trust and self-efficacy play a partial mediating role in this relationship.

Breaking down the total indirect effect, several specific mediation pathways were found to be significant.

Indirect effect via Political Trust (Di → Pt → Dv): The estimated standardized indirect effect through political trust was 0.054 (95% CI = 0.023, 0.070), with the confidence interval not including zero. This supports Hypothesis 2 and indicates that political trust acts as a single mediator in this relationship (accounting for approximately 17.17% (0.054/0.315) of the total effect, calculated based on standardized effects).

Indirect effect via Self-Efficacy (Di → Se → Dv): The estimated standardized indirect effect through self-efficacy was 0.052 (95% CI = 0.026, 0.073), with the confidence interval not including zero. This confirms Hypothesis 3 and the mediating role of self-efficacy (accounting for approximately 16.53% (0.052/0.315) of the total effect, calculated based on standardized effects).

Sequential Indirect Effect (Di → Pt → Se → Dv): A significant serial mediation path was identified, with an estimated standardized sequential indirect effect of 0.018 (95% CI = 0.005, 0.023), with the confidence interval also not including zero. This provides strong support for Hypothesis 4, highlighting a sequential mediating process where digital literacy influences political trust, which in turn affects self-efficacy, and subsequently impacts digital village participation (accounting for approximately 5.58% (0.018/0.315) of the total effect, calculated based on standardized effects).

These findings, demonstrating both a significant direct influence and important mediated pathways through psychological and attitudinal factors such as political trust and self-efficacy, are broadly consistent with existing literature on the socio-psychological determinants of digital engagement and participation[120]. Prior research has highlighted how individual beliefs, confidence in one's abilities (self-efficacy), and trust in institutions can shape engagement with digital platforms and civic processes[121]. Our results specifically corroborate these perspectives by empirically confirming that digital literacy not only directly enhances participation but also indirectly fosters it by potentially increasing political trust and bolstering self-efficacy among rural left-behind women in the context of digital villages. This is particularly relevant in the digital village context, where both the perceived trustworthiness of the digital environment (political trust) and an individual's belief in their capacity to effectively use digital tools (self-efficacy) are crucial for overcoming barriers and actively participating.

Moreover, SEM allows for a more rigorous comparison of effects. By examining the standardized path coefficients and their relative contributions, we observe that the direct effect (standardized coefficient = 0.191) appears numerically larger than the total indirect effect (standardized coefficient = 0.124). While both pathways are significant, this suggests that the direct empowerment gained through digital literacy skills remains the primary driver of participation. However, the substantial and significant indirect effects through political trust and self-efficacy underscore the critical role of these psychological factors as important leverage points for interventions aimed at increasing digital village participation, especially given their sequential nature. Future research could further explore the contextual boundary conditions under which these pathways operate more prominently.

Conclusion and implications

Based on field survey data collected from left-behind women in rural areas of four cities in Shaanxi Province, supported by a major project of the National Social Science Fund of China, this study systematically investigated the impact mechanisms and complexities of digital literacy on the digital village participation of rural left-behind women, employing chain mediation models, Tobit models, and CQR models. The main conclusions and implications are as follows:

Main research conclusions

Through multi-model and multi-dimensional empirical analysis, this study reveals the core role of digital literacy in driving the integration of rural left-behind women into the digital village process, the heterogeneous characteristics of its impact, and its deep psychological transmission mechanisms. Simultaneously, it clarifies the complex influence of other key socio-economic factors.

First, digital literacy is a key driving force empowering rural left-behind women to participate in digital village construction, but its influence exhibits significant domain specificity. The research consistently found that digital literacy can significantly enhance the degree and level of participation of left-behind women in the overall digital village, digital economy, and digital governance. However, in the specific domain of digital agricultural services for public well-being, the direct promoting effect of digital literacy was not prominent, suggesting that digital participation in this area may follow a unique logic and driving path distinct from other domains.

Second, the empowering effect of digital literacy on digital village participation is not uniformly consistent but presents significant heterogeneous characteristics depending on the individuals' existing participation levels. CQR analysis further deepened this understanding: the impact trajectory of digital literacy on overall digital village participation shows an "inverted U-shape," with its marginal effect being most significant among women with moderate participation levels. Its impact on digital economy participation exhibits a "U-shape" characteristic, being more prominent among women at both low and high ends of participation levels. Conversely, its influence on digital governance participation gradually weakens as participation levels increase, with the most substantial uplifting effect observed for low-participation groups. This finding challenges the "averaged" and "homogenized" assumptions regarding the impact of digital literacy.

Third, the influence of digital literacy on digital village participation extends beyond direct pathways; more importantly, it operates indirectly by shaping key psychological variables such as individuals' political trust and self-efficacy. Chain mediation effect analysis confirmed that political trust and self-efficacy play important partial mediating roles between digital literacy and digital village participation. Particularly noteworthy is the identification of a sequential mediation path: "digital literacy → political trust → self-efficacy → digital village participation," which clearly reveals the intrinsic mechanism through which digital literacy promotes final participation behavior via a chain transmission of positive psychological states.

Fourth, apart from digital literacy, other individual, family, and socio-economic factors also exert complex and domain-differentiated influences on the digital village participation of left-behind women. Factors such as political trust, self-efficacy (when acting as a direct influence), personal characteristics, and family support often have a positive promotional effect on overall participation, digital economy, and digital governance participation. Conversely, certain family economic conditions (e.g., spouse's income) and family structure factors (e.g., number of elderly individuals in the household) may act as constraints. Particularly in the domain of digital agricultural services for public well-being, many traditional socio-economic factors that are significant in other domains (such as women's age, political affiliation, spouse's monthly income, eldest child's monthly income, and number of elderly individuals in the household) did not show significant associations. This once again corroborates the uniqueness of digital agricultural service adoption, suggesting that its influencing factors urgently require more in-depth, specialized investigation.

Theoretical and practical implications

Theoretical contributions

The findings of this study make several important contributions to deepening the understanding of the digital divide, digital inclusion, and related theories:

Firstly, by empirically revealing the "domain specificity" within digital village participation and the "individual heterogeneity" of digital literacy's impact, this study challenges the traditional perception of digital village participation as a singular, homogenized concept. It promotes a profound understanding of the complexity and context-dependency of the digital divide. Specifically, the unique picture presented by the domain of digital agricultural services for public well-being, and the differentiated impact patterns revealed by CQR, strongly call for academia to construct more refined, multi-dimensional, and dynamic theoretical frameworks for digital inclusion, thereby moving beyond existing "one-size-fits-all" or overly simplified theoretical models.

Secondly, by identifying and validating the mediating mechanisms of political trust and self-efficacy in the process of digital literacy influencing digital participation, this study makes a pivotal theoretical contribution by

synergistically integrating the micro-level explanatory power of the SOR theory with the macro-level contextual insights of the STS theory into the digital divide research framework. Our findings not only empirically support the SOR model by demonstrating how digital literacy (Stimulus) influences participation (Response) through political trust and self-efficacy (Organism), but critically, they also contextualize these psychological processes within the broader socio-technical environment. This integration elucidates that digital literacy does not simply translate skills directly into participation behavior. Rather, it indirectly drives participation by influencing and shaping individuals' intrinsic cognitive and psychological states (such as the establishment of trust and the enhancement of efficacy), which are themselves profoundly shaped by the interplay between the social and technical subsystems of the digital village, as posited by STS theory. Consequently, this study greatly enriches and deepens the understanding of the empowering pathways and intrinsic logic of digital literacy, emphasizing the paramount importance of focusing on both individual psychological factors and the broader socio-technical context in the digital inclusion agenda. This integrated perspective moves beyond traditional disciplinary silos, offering a more holistic and robust lens for understanding digital empowerment.

Policy recommendations

Based on the above research conclusions, to more effectively promote the digital village participation of rural left-behind women and bridge the digital divide, this study proposes the following targeted policy recommendations:

First, while continuously strengthening universal education in digital literacy, it is imperative to implement more precise and differentiated empowerment strategies that fully consider differences in participation domains and individual levels. Policymaking should transcend "one-size-fits-all" digital skills training models. Specialized promotion and support schemes should be developed for participation "lowlands" such as digital agricultural services for public well-being. Concurrently, based on women's existing participation levels in different digital domains (e.g., low and high-end groups in the digital economy domain, low-participation groups in the digital governance domain), differentiated digital literacy enhancement content, support measures, and incentive mechanisms should be designed and provided.

Second, policy interventions need to move beyond mere skills training and strive to construct an integrated "digital skills enhancement—political trust cultivation—self-efficacy strengthening" tripartite comprehensive empowerment system. This implies, on one hand, continuing to improve women's digital operational skills and information discernment abilities. On the other hand, it is even more crucial to actively build and maintain women's political trust in digital systems and related governance by enhancing the transparency, reliability, and usability of digital village services. Furthermore, through creating practical opportunities, providing role models, and reinforcing positive feedback, their confidence and efficacy in using digital tools to improve their own production and lives should be genuinely enhanced.

Third, pay close attention to and actively intervene in the various socio-economic structural factors affecting digital participation, fostering a more favorable external support environment. Policies should focus on identifying and fully utilizing factors that positively influence digital participation (such as rural social support networks, harmonious family relationships, and support systems), and promoting successful experiences. Simultaneously, it is necessary to confront and strive to alleviate negative factors constraining women's digital participation (such as heavy family care burdens, the fetters of traditional gender concepts, and certain family economic pressures). This can be achieved, for example, by developing rural public childcare services and advocating for gender equality, thereby clearing obstacles for women's participation in digital village construction.

Summary

In summary, grounded in the practical context of China's rural development, this study systematically reveals the direct impact, heterogeneous effects, and deep psychological transmission mechanisms of digital literacy on the digital village participation of rural left-behind women. It profoundly elucidates the core status and complex characteristics of digital literacy in promoting digital inclusion and rural revitalization. The research conclusions not only provide new theoretical perspectives and solid empirical evidence for understanding the digital integration dilemmas and empowerment pathways of vulnerable groups in the digital age but also contribute important academic insights and practical references for all levels of government in formulating more precise, inclusive, and effective Digital Village Development policies and digital feedback strategies. This, in turn, will promote coordinated urban-rural digital development, bridge the widening digital divide, and ultimately contribute to achieving the goal of common prosperity.

Limitations and future research

Despite its systematic exploration, this study has limitations warranting future attention. First, its single-region sample (Shaanxi Province) restricts the universal applicability of findings, given rural disparities in infrastructure, economic development, and policy. Future research, potentially using comparative or multi-level designs, should investigate regional heterogeneity to inform differentiated, precise policies, avoiding "one-size-fits-all" interventions.

Second, digital infrastructure (e.g., network access quality, equipment availability), a fundamental precondition, was not fully incorporated. Future work should integrate such infrastructure variables into analytical frameworks to assess their constraining effects on digital capabilities and participation.

Furthermore, this study offered a relatively limited exploration of how demographic characteristics (e.g., age, education) shape digital literacy acquisition and application. Future research should conduct more granular analyses of digital literacy's manifestations and impact across diverse demographic segments, supporting more targeted digital empowerment. This could also extend to exploring the unique adoption barriers for specific applications like digital benefit services, a key finding of this study.

In conclusion, future research, ideally employing mixed-methods or longitudinal approaches, needs to examine digital literacy's influence mechanisms with greater nuance. This involves integrating multidimensional regional/individual differences and key contextual factors (including infrastructure and socioeconomic variables, and other potential mediators/moderators). Such endeavors are vital for advancing rural digital development policies towards being more scientific, rational, and effective, while also enriching theoretical models of digital inclusion.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Declarations

Competing interests

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