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The emergence of the Fourth Industrial Revolution has accelerated the integration of digital technologies, including artificial intelligence (AI), robotics, big data analytics, and the Internet of Things (IoT), into global production systems (Almarashdi et al., 2026; Dalgaldere, 2025; Rulandari & Silalahi, 2025). Agriculture, historically characterized by labour-intensive practices and traditional knowledge systems, is increasingly undergoing a technological transformation through what is commonly referred to as Agriculture 4.0 (Abbasi et al., 2022). This paradigm encompasses precision farming, sensor-based monitoring, autonomous machinery, data-driven decision-making, and digital supply chains aimed at improving productivity, efficiency, and sustainability within agrifood systems (Eze et al., 2025). Digital agriculture technologies are rapidly reshaping agricultural production systems by enabling real-time data collection, automated crop management, and predictive analytics to optimize yields and resource use (Aarif KO et al., 2025). Governments and international organizations increasingly promote these innovations as essential pathways to address global challenges such as food security, climate change, and rural development.

However, while Agriculture 4.0 promises increased efficiency and competitiveness, it also raises important socio-economic questions regarding labour transformation, rural livelihoods, and social equity (Hertini & Risdiyanto, 2025). Automation technologies, such as autonomous tractors, agricultural drones, and AI-based crop monitoring systems, have the potential to significantly alter agricultural labour processes by replacing manual tasks traditionally performed by human workers (Noor et al., 2021; Sarker et al., 2025). Recent studies suggest that the digitalization of agriculture is reshaping the organization of work in farming systems and creating new forms of labour relations, including data management roles, digital advisory services, and technology-mediated farm management (Nettle et al., 2025). At the same time, scholars warn that the adoption of robotics and automation may displace traditional agricultural labour while simultaneously creating new forms of specialized technical employment that are often inaccessible to marginalized rural populations (Gava et al., 2025). These structural transformations highlight the need to critically examine how digital technologies reshape labour markets in rural economies.

Despite the rapid growth of digital agriculture research, much of the existing scholarship focuses on technological innovation, productivity gains, and economic efficiency while paying comparatively limited attention to the social and gendered dimensions of agricultural labour (Hertini & Risdiyanto, 2025; Nettle et al., 2025). Agricultural production in many parts of the Global South remains deeply structured by gendered divisions of labour, where women frequently perform essential yet undervalued tasks within farming systems. Women are often heavily involved in planting, harvesting, post-harvest processing, food preparation, and local market distribution, but their labour contributions remain insufficiently recognized within formal economic and policy frameworks (Chandel et al., 2025). Recent scholarship highlights that women's participation in agriculture is not only extensive but also increasingly central to rural economies, particularly as male labour migrates toward non-agricultural sectors. Indeed, the phenomenon commonly referred to as the "feminisation of agriculture" has been widely documented, where women increasingly constitute the majority of agricultural labourers in many rural regions (Mugion et al., 2026).

Nevertheless, the expansion of women's participation in agricultural labour does not necessarily translate into improved economic empowerment or decision-making power (Tripura & Rakhi, 2026). Structural inequalities, including unequal access to land ownership, credit, digital technologies, and agricultural training, continue to limit women's capacity to benefit from agricultural modernization (Sikdar & Anand, 2025). In many regions, women remain concentrated in low-paid and informal forms of agricultural labour despite their central contributions to food production (Shrestha et al., 2024). Recent analyses indicate that women may account for a majority of agricultural labour in certain regions while owning only a small fraction of agricultural land, illustrating persistent gender disparities within rural economies (Ossome, 2025). As agriculture becomes increasingly digitized, scholars emphasize that technological innovation may reproduce or even exacerbate existing gender inequalities if gender-responsive policies are not incorporated into digital transformation strategies (Akello & Brunori, 2025; Gupta, 2026).

At the same time, digital agricultural transformation does not occur uniformly across rural contexts. Local communities often negotiate technological adoption through social norms, cultural practices, and community-based decision-making processes (Schaefer et al., 2021). In many traditional agricultural systems, farmers selectively adopt digital technologies rather than implementing full automation across all stages of production (Sumberg & Giller, 2022). Such selective adoption reflects attempts to balance technological efficiency with the preservation of rural livelihoods and social stability. Evidence from horticultural agriculture in Cianjur Regency illustrates how farmers integrate elements of Industry 4.0 primarily within post-harvest processing and digital marketing activities while maintaining manual practices in cultivation stages such as land preparation, planting, and harvesting (Andang et al., 2026; Singh et al., 2022). This hybrid model demonstrates how local wisdom and

community knowledge systems shape technological transitions in ways that protect employment and maintain social cohesion within rural communities (Katz, 2026).

Traditional workforce planning theories, such as the labour supply-demand framework, generally predict that technological automation reduces labour demand and leads to workforce restructuring or displacement (Aji & Akbardin, 2024). Yet empirical evidence from rural contexts suggests that technological adoption is not purely determined by economic rationality (Coker, 2026). Instead, communities frequently negotiate technological change through culturally embedded practices that prioritize social welfare and livelihood security (Fonchingong Che & Bang, 2024). These dynamics highlight the limitations of conventional workforce planning models when applied to rural agricultural contexts where social norms, community institutions, and local knowledge significantly influence economic decision-making (Prajapati et al., 2025). Importantly, the intersection between digital agricultural transformation, local wisdom, and gendered labour relations remains underexplored in contemporary scholarship. While existing studies examine the technological aspects of Agriculture 4.0, fewer analyses investigate how digitalization interacts with gender inequalities, rural governance structures, and labour hierarchies.

From a feminist political economy perspective, technological transformation cannot be understood solely as a process of economic modernization; rather, it represents a broader socio-political restructuring that redistributes power, resources, and opportunities across gendered labour systems (Webb, 2026; Zheng et al., 2023). As scholars increasingly emphasize, digital agriculture should therefore be examined through critical lenses that address social inclusion, gender equality, and equitable access to technological innovation (Carolan, 2025; Mugion et al., 2026). Against this backdrop, this study investigates the digital transformation of horticultural agriculture in Indonesia through the combined perspectives of local wisdom, gendered labour relations, and workforce planning. By examining how rural communities selectively adopt Industry 4.0 technologies while maintaining traditional labour practices, the study explores how technological modernization intersects with gendered labour structures and rural governance systems. Specifically, the research seeks to understand how local agricultural communities mediate technological change in order to preserve employment opportunities and how these processes affect the gender dynamics of agricultural labour. Unlike much of the existing Agriculture 4.0 literature, which primarily emphasizes technological adoption, productivity gains, or innovation efficiency, this study advances a broader socio-political understanding of digital agricultural transformation. Specifically, the research develops an interdisciplinary analytical perspective integrating workforce planning theory, feminist political economy, and governance analysis to examine how technological change reshapes labour systems, gender relations, and institutional practices within rural communities. By foregrounding these interconnected dimensions, the study contributes to emerging debates on inclusive digital transformation and socially embedded agricultural modernization.

The study addresses three key research questions:

1. How does the implementation of Industry 4.0 technologies reshape labour structures within horticultural agriculture?
2. In what ways do local wisdom and community practices mediate the impacts of digital transformation on rural employment?
3. What gendered implications emerge from the selective adoption of digital technologies within agricultural production systems?

These research questions are analytically informed by the study's three complementary theoretical lenses. Workforce planning theory guides the examination of labour restructuring, skill transformation, and changing employment demands under Agriculture 4.0. Feminist political economy informs the analysis of gendered labour dynamics, inequalities in technological access, and differentiated participation within agricultural production systems. Governance analysis provides a framework for understanding how institutions, policies, and local community structures mediate technological adoption and shape labour outcomes within rural contexts. By addressing these questions, this research contributes to emerging debates on digital transformation, gender equality, and inclusive rural development. The paper argues that the transition toward Agriculture 4.0 must move beyond purely technological considerations and incorporate gender-sensitive workforce planning and inclusive governance frameworks that recognize the socio-cultural dynamics shaping rural labour systems. Understanding how local communities negotiate technological change provides valuable insights for designing policies that promote both technological innovation and social justice in the evolving landscape of digital agriculture.

LITERATURE REVIEW

Agriculture 4.0 and labour transformation

Agriculture 4.0 refers to the integration of advanced digital technologies, such as artificial intelligence (AI), Internet of Things (IoT), robotics, sensors, and data analytics, into agricultural production and agrifood systems

(Mugion et al., 2026). Recent scholarship conceptualizes it not merely as mechanization, but as a socio-technical transformation that restructures production processes, decision-making, and institutional arrangements across the value chain (Durán et al., 2023). This shift highlights that digital agriculture is embedded within governance systems, infrastructure, and socio-political contexts rather than being a purely technological evolution (de Avila & Barbosa, 2025). A key consensus in recent literature is that Agriculture 4.0 does not simply replace labour; it reconfigures it. Digital technologies redistribute tasks by reducing manual activities while increasing cognitive and managerial demands, such as data interpretation, system monitoring, and platform coordination. Manzoor et al. (2025) demonstrates that these transformations occur across multiple levels, farmers, workers, advisory systems, and value chains, resulting in differentiated outcomes including deskilling, upskilling, and task intensification. Similarly, Ahmadi et al. (2025) shows that digital tools reshape farm work by introducing new knowledge regimes and managerial practices, often accompanied by increased reliance on data-driven decision-making. Empirical evidence further supports this reconfiguration perspective. Chandel et al. (2024) find that smart farming technologies reduce repetitive labour but simultaneously generate new responsibilities such as troubleshooting, calibration, and continuous system oversight. Importantly, labour transformation extends beyond farm workers to include advisers and intermediaries, whose roles increasingly involve translating digital outputs into actionable farming decisions (Nettle et al., 2025). Thus, Agriculture 4.0 creates new occupational structures rather than eliminating labour outright. However, these transformations are highly uneven. Adoption remains constrained by high costs, infrastructure gaps, limited digital literacy, and weak policy support, particularly in developing contexts (Carolan, 2025). These barriers shape who benefits from digitalization and who is excluded, reinforcing structural inequalities in labour markets. As a result, labour outcomes vary significantly across regions, farm sizes, and institutional environments.

Recent studies also shift attention from job quantity to quality of work. Digital agriculture can enhance efficiency and transparency but may also intensify labour, increase surveillance, and alter power relations. Manzoor et al. (2025) highlight that AI-driven systems can embed monitoring mechanisms that reshape worker autonomy, while broader reviews stress risks related to precarious employment and weakened labour protections. This has led to growing calls to evaluate Agriculture 4.0 through a “decent work” lens, emphasizing dignity, safety, and equity alongside productivity. Moreover, emerging research underscores the importance of skills and capability formation. Digital transformation requires new technical and analytical competencies, making education and training central to labour adaptation. Persistent digital divides mean that access to skills development significantly influences participation in digital agriculture (Shen et al., 2022). Hence, Agriculture 4.0 should be understood as a process of labour restructuring shaped by technology, institutions, and human capabilities. This perspective is particularly relevant for labour-intensive systems such as horticulture in emerging economies, where digital adoption is likely to be selective and socially mediated

Gender, feminisation of agriculture, and rural inequality

The feminisation of agriculture describes the rising participation of women in agricultural labour, driven largely by male outmigration, rural restructuring, and shifting livelihood strategies (Mugion et al., 2026). Recent studies confirm that women now constitute a substantial share of the agricultural workforce in developing regions, yet their contributions remain under-recognized due to informal roles and unpaid family labour (Agarwal et al., 2024). This trend reflects not only increased visibility but also deeper structural transformations in rural economies. Importantly, feminisation does not automatically imply empowerment. Contemporary research emphasizes that women’s growing participation often coexists with persistent inequalities in access to land, credit, and decision-making. Women typically remain excluded from ownership and control of productive assets, which limits their bargaining power and participation in farm management (Sikdar & Anand, 2025). As a result, feminisation is frequently associated with labour intensification under constrained resources, rather than improved socio-economic status. These inequalities are embedded within institutional frameworks. Agricultural extension services, financial systems, and training programs continue to be male-oriented, restricting women’s access to knowledge and innovation (Doss, 2025). Consequently, women face structural barriers in adopting modern agricultural practices and participating in higher-value markets. This marginalization becomes more pronounced in labour-intensive sectors such as horticulture, where women dominate low-paid and invisible tasks such as grading, packaging, and post-harvest handling (Akello & Brunori, 2025). The rise of digital agriculture introduces new dynamics into these gendered inequalities. While Agriculture 4.0 technologies offer opportunities for efficiency and market access, they also risk reinforcing the digital gender divide. Women are significantly less likely to access smartphones, digital platforms, and technical training, limiting their participation in data-driven agriculture (Akello & Brunori, 2025). This exclusion can concentrate technological benefits among male farmers and larger enterprises, exacerbating existing disparities (Carolan, 2025).

However, digitalization also holds transformative potential if inclusively governed. Emerging evidence shows that digital platforms can enhance women’s access to market information, facilitate direct sales, and reduce

dependency on intermediaries (Malhotra & Anand, 2020). Mobile-based tools and e-commerce systems can improve income opportunities and strengthen women's economic agency (Atinaf et al., 2023). Thus, digital technologies function as both mechanisms of exclusion and empowerment, depending on access, design, and policy support. Feminist political economy perspectives emphasize that these outcomes are shaped by broader systems of power, labour relations, and institutional arrangements. Technological change is not neutral; it redistributes opportunities and risks across gendered labour systems. Local socio-cultural norms further mediate these processes, influencing how technologies are adopted and integrated into existing practices (Sultana, 2017). Evidence from rural contexts demonstrates that adoption is often selective. Farmers balance productivity gains with concerns about employment and community stability, maintaining labour-intensive practices while integrating digital tools in areas such as marketing. This highlights the role of local agency in shaping technological transitions (Ronzhin et al., 2025). Overall, gender inequalities remain central to understanding agricultural transformation. Without gender-responsive policies, digital agriculture risks deepening rural inequality. Inclusive strategies must therefore address structural barriers, enhance women's access to resources and skills, and ensure equitable participation in technological change.

Feminist political economy and governance of digital agriculture

Feminist political economy (FPE) provides a critical framework for understanding how technological transformations in agriculture are shaped by power relations, institutional structures, and gendered inequalities (Mackay et al., 2010). Rather than viewing digital agriculture as a neutral process of modernization, FPE highlights how economic systems depend on unequal distributions of labour, resources, and decision-making authority (Elson, 2023; Fraser et al., 2024). This perspective is essential for analyzing Agriculture 4.0, where digital technologies are embedded within existing socio-economic hierarchies. A central insight of FPE is the recognition of invisible and undervalued labour, particularly women's unpaid or informal work. Agricultural systems rely heavily on such labour for activities including post-harvest processing, subsistence production, and household food security, yet these contributions remain largely excluded from formal economic accounting (Fraser et al., 2024). Digital transformation may alter production processes, but it does not automatically address these underlying inequalities in labour recognition or compensation. Structural inequalities in access to resources further shape participation in digital agriculture. Land ownership, capital, and institutional representation remain key determinants of economic power. Women's limited access to land and financial resources restricts their ability to invest in and benefit from digital technologies (Agarwal et al., 2024). As a result, technological adoption often reflects existing hierarchies rather than transforming them.

The rise of Agriculture 4.0 also introduces new forms of digital governance. Data platforms, algorithmic systems, and digital infrastructures increasingly influence agricultural decision-making and market participation (Carolan, 2025). These developments raise critical questions about data ownership, control, and access. From an FPE perspective, digital governance can concentrate power among technology providers, large-scale producers, and platform operators, potentially marginalizing smallholders and women farmers. At the same time, digital systems can create new opportunities for inclusion. Digital marketplaces, mobile applications, and online training platforms can reduce information asymmetries and expand access to markets, particularly for marginalized groups (Rotz et al., 2019). However, these benefits depend on equitable access to infrastructure, digital literacy, and institutional support. Without such conditions, digitalization risks reinforcing exclusion (Mansoor, 2021). This has led to growing emphasis on inclusive and gender-responsive governance. Recent research stresses the need for policies that integrate gender considerations into digital agriculture, including targeted training, improved access to credit and land, and investments in digital infrastructure (Gava et al., 2025). Participatory governance approaches are also critical to ensure that technological transitions reflect the needs and priorities of rural communities. Feminist political ecology complements this perspective by highlighting the role of local knowledge and community institutions. Technological adoption is not purely market-driven; it is shaped by cultural norms, social relations, and ecological practices (Akello & Brunori, 2025; Levkoe et al., 2023). Farmers often adopt technologies selectively, balancing efficiency with concerns about employment and social cohesion. Overall, integrating feminist political economy into digital agriculture shifts the focus from technological efficiency to equity, power, and governance (Chandel et al., 2025). It emphasizes that sustainable agricultural transformation requires not only innovation but also institutional reforms that promote gender equality, labour inclusion, and social justice.

Integrating workforce planning, feminist political economy, and governance perspectives

While workforce planning theory, feminist political economy, and governance analysis are often discussed independently, this study adopts an integrated analytical perspective to explain digital agricultural transformation within rural labour systems. Workforce planning theory provides a foundation for understanding how

technological change reshapes labour demand, skill requirements, and employment structures under Agriculture 4.0. However, conventional workforce models alone cannot fully explain labour outcomes in rural contexts where technological adoption is mediated by social relations and institutional arrangements. Feminist political economy complements this perspective by examining how technological change interacts with gendered inequalities in access to resources, labour participation, and decision-making authority. Governance analysis further situates these processes within multi-level institutional systems involving state policies, farmer organizations, cooperatives, and community practices. Taken together, these perspectives suggest that digital agricultural transformation is not merely a technical process of labour automation but a negotiated socio-political process in which governance structures and workforce dynamics jointly shape gendered labour outcomes. Despite growing scholarship on Agriculture 4.0, significant gaps remain in understanding how digital agricultural transformation intersects simultaneously with workforce restructuring, gendered labour dynamics, and governance processes within localized agricultural settings. Existing studies often privilege technological efficiency, productivity, or adoption behaviour, while giving comparatively less attention to how communities negotiate digital change through local institutions, labour priorities, and gendered socio-economic realities. Addressing this gap, the present study advances digital agriculture scholarship by integrating workforce planning theory, feminist political economy, and governance analysis to examine how technological transitions are socially mediated within Indonesia's horticultural sector.

METHODOLOGY

Research design

This study adopts a qualitative research design combining policy analysis, institutional analysis, and secondary data interpretation to examine how digital agricultural transformation intersects with gendered labour structures and local governance practices. Qualitative approaches are particularly appropriate for exploring complex socio-economic phenomena where technological change interacts with cultural norms, institutional arrangements, and community practices (Creswell & Creswell, 2017). In the context of this research, qualitative analysis enables a deeper understanding of how digital agricultural technologies are negotiated and adapted within rural communities rather than assuming a uniform process of technological diffusion. The research focuses on the horticultural agricultural sector in Indonesia, with particular attention to the case of Cianjur Regency in West Java Province. This region represents a significant agricultural production area where horticulture plays a central role in both employment and regional economic development. The sector contributes substantially to agricultural exports and employs a large share of the rural workforce, making it an important site for examining how technological modernization interacts with labour dynamics and rural livelihoods. The case study approach allows the study to explore the social and institutional processes that shape the adoption of Industry 4.0 technologies within a specific agricultural context. The analytical framework of the study integrates three complementary perspectives: workforce planning theory, feminist political economy, and rural governance analysis. Workforce planning theory provides insights into how technological changes influence labour demand and supply dynamics within agricultural production systems. Feminist political economy contributes a critical lens for examining how gendered power relations influence access to resources, labour opportunities, and decision-making within rural economies. Finally, governance analysis allows the study to investigate how institutional structures and policy frameworks shape technological transitions in agriculture. By combining these perspectives, the study aims to move beyond purely technocratic analyses of digital agriculture and instead highlight the socio-political dimensions of technological change.

Data sources

The study relies primarily on secondary data sources, complemented by insights derived from policy documents and institutional reports related to agricultural development and digital transformation. Secondary data are particularly valuable for examining structural patterns of labour participation, technological adoption, and governance arrangements across agricultural sectors. Three main categories of data sources were used in this study:

Policy and institutional documents: National, provincial, and regional policy documents were examined to understand how digital agricultural transformation is framed within public policy. These include development planning documents, agricultural strategies, and digitalization initiatives related to Industry 4.0 and agricultural modernization. Such documents provide insights into government priorities, institutional responsibilities, and policy narratives surrounding technological adoption in agriculture. In Indonesia, national initiatives such as Making Indonesia 4.0 emphasize the role of technological innovation in strengthening industrial competitiveness and improving productivity across key sectors, including agriculture. Regional planning documents also provide

important insights into how these national priorities are translated into local governance strategies and agricultural programs.

Agricultural and labour statistics: Statistical data from national and regional agencies were used to contextualize the role of horticultural agriculture within regional labour markets. These data provide information on employment patterns, agricultural production levels, and demographic characteristics of the agricultural workforce. In Cianjur Regency, for example, a substantial proportion of the population is employed in horticultural agriculture, reflecting the sector's importance for rural livelihoods and regional economic development. These statistical sources help situate the study within broader structural patterns of agricultural employment and allow the analysis to examine how digital agricultural policies intersect with existing labour dynamics.

Academic and institutional literature: The study also draws extensively on academic literature, international reports, and institutional analyses related to digital agriculture, gender and rural labour, and agricultural governance. These sources provide theoretical insights and comparative perspectives that help situate the case study within broader global debates on digital transformation and rural development. The interpretation of policy documents and secondary materials followed a structured qualitative analytical procedure. Documents were selected based on their relevance to digital agricultural transformation, labour dynamics, gender participation, and governance arrangements within the Indonesian agricultural context. The analytical process involved identifying recurring themes and analytical categories aligned with the study framework, including labour restructuring, technological adoption, gendered participation, institutional coordination, and local mediation practices. Through iterative comparison across policy, institutional, and secondary sources, the study examined consistencies, variations, and governance gaps shaping Agriculture 4.0 implementation.

Analytical framework

To analyze the interaction between digital agricultural transformation and gendered labour systems, the study employs a three-stage analytical approach.

Policy tracing: The first stage involves tracing the development of digital agricultural policies and technological initiatives across different levels of governance. Policy tracing examines how national modernization strategies related to Industry 4.0 are translated into regional agricultural programs and institutional initiatives. This analysis helps identify gaps between policy intentions and practical implementation within rural contexts.

Institutional analysis: The second stage focuses on examining the roles of key government institutions involved in agricultural development, labour management, and digital infrastructure. Institutional analysis explores how responsibilities are distributed across agencies and how coordination between institutions influences the implementation of digital agricultural initiatives. Previous research highlights that agricultural digitalization often requires collaboration between multiple sectors, including agriculture, labour, information technology, and economic development agencies. Understanding these institutional relationships is therefore essential for assessing the governance of technological transformation.

Socio-economic interpretation: The final stage involves interpreting the socio-economic implications of digital agricultural transformation for rural labour systems. Drawing on feminist political economy perspectives, the analysis examines how technological adoption may reshape labour relations, employment opportunities, and gender dynamics within agricultural production systems. Particular attention is given to how local wisdom and community practices mediate technological adoption. Rather than assuming that digital technologies automatically replace labour, the analysis explores how farmers negotiate technological transitions in ways that balance productivity gains with social considerations such as employment stability and community welfare.

RESULTS AND DISCUSSION

Digital transformation and rural labour restructuring

Digital technologies, such as AI, IoT, robotics, and data analytics, are fundamentally reshaping agricultural production by enabling real-time monitoring and data-driven decision-making (Rulandari & Silalahi, 2025; Aarif et al., 2025). The findings of this study show that this transformation does not lead to straightforward labour displacement; instead, it produces a reconfiguration of labour systems, consistent with recent research on Agriculture 4.0 (Nettle et al., 2025). Across the horticultural sector, digitalization has resulted in the emergence of hybrid production systems, where automated and manual practices coexist. Technologies are primarily applied to mechanizable functions such as post-harvest sorting, irrigation control, and market coordination, while labour-intensive tasks, particularly planting, crop maintenance, and harvesting, continue to depend on human labour. This uneven adoption reflects both technological constraints and the socio-economic realities of smallholder farming, supporting the argument that digital transformation redistributes rather than replaces labour (Gava et al., 2025). At the same time, the findings reveal the expansion of new forms of labour associated with digital

systems. Farmers and workers increasingly engage in activities such as data monitoring, equipment supervision, and digital platform management. This shift signifies a transition from predominantly physical labour toward more knowledge-intensive and technical roles, extending beyond farms to include actors involved in logistics, advisory services, and digital marketing.

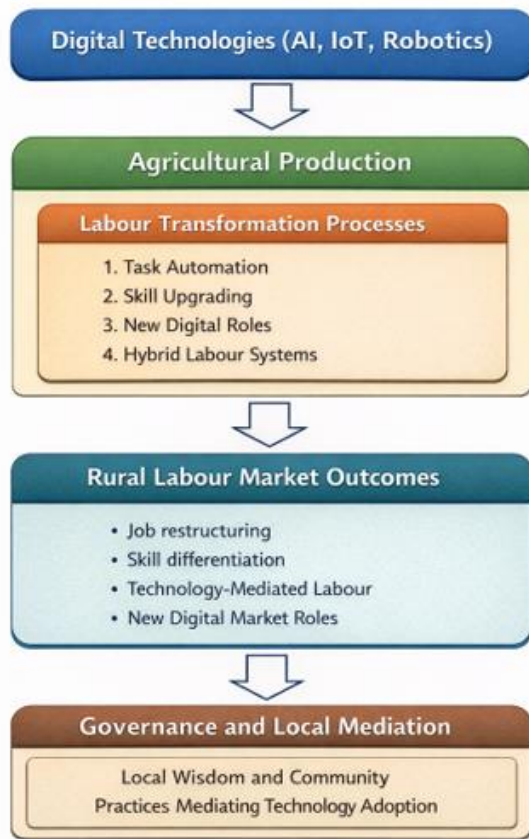
As summarized in **Table 1**, while certain technologies reduce manual labour requirements, they simultaneously generate new tasks related to data interpretation, system maintenance, and digital coordination. This dual effect reinforces the notion that Agriculture 4.0 transforms the composition of labour rather than eliminating it. The restructuring of labour is closely linked to changing skill demands. Digital agriculture requires competencies in information technology, data analysis, and system management, creating new opportunities within agricultural value chains. However, the findings also highlight significant inequalities in access to these skills. Smallholder farmers often face barriers related to limited infrastructure, financial constraints, and low digital literacy, restricting their ability to adopt and benefit from technological innovations. This aligns with concerns that digital transformation may deepen existing disparities if not supported by inclusive governance and capacity-building initiatives (Hertini & Risdwiyanto, 2025). Importantly, the Indonesian case demonstrates that technological adoption is not purely driven by efficiency considerations but is shaped by local wisdom and community priorities. Farmers selectively integrate digital tools in areas such as marketing and post-harvest processing while maintaining manual labour in cultivation stages to preserve employment and social stability. This reflects a socially embedded approach to technological change, where innovation is negotiated rather than imposed. From a workforce planning perspective, these findings suggest that digital agricultural transformation does not produce linear labour substitution but rather a reconfiguration of labour demand, skill formation, and occupational roles. The emergence of hybrid labour systems reflects adaptive workforce dynamics shaped by local socio-economic realities rather than purely technological efficiency.

Table 1

Digital agricultural technologies and labour restructuring in agriculture 4.0

Technology	Stage of Agricultural Production	Labour Impact	Skills Required	References
Precision agriculture sensors	Crop monitoring	Reduces manual field inspection	Data interpretation, sensor management	Aarif et al., 2025
Agricultural drones	Crop surveillance and pesticide application	Reduces labour in monitoring and spraying	Drone operation, remote sensing	Sarker et al., 2025
Autonomous tractors	Land preparation	Reduces manual machinery operation	Equipment supervision, technical maintenance	Abbasi et al., 2022
AI-based crop analytics	Farm management decisions	Supports managerial decision-making	Data analysis and digital literacy	Eze et al., 2025
Digital farm management systems	Production planning	Enhances coordination and monitoring	Software operation, data interpretation	Nettle et al., 2025
Smart irrigation systems	Irrigation control	Reduces manual irrigation tasks	IoT management, technical maintenance	Aarif et al., 2025
Automated sorting and grading	Post-harvest processing	Reduces labour for product classification	Machine operation and monitoring	Chandel et al., 2025
Digital marketing platforms	Agricultural product sales	Expands market access for farmers	Digital marketing skills	Singh et al., 2022
Blockchain traceability systems	Supply chain management	Creates new logistics and data roles	Digital traceability systems	Prajapati et al., 2025
Agricultural data platforms	Farm analytics and forecasting	Generates new knowledge work roles	Data analytics and interpretation	Islam et al., 2024

To conceptualize the relationship between digital technologies and labour restructuring in Agriculture 4.0, **Figure 1** presents the analytical framework.

Figure 1*Conceptual framework of digital transformation and labour restructuring in agriculture 4.0*

The framework in [Figure 1](#) highlights that technological transformation in agriculture is mediated by governance systems and community practices. Rather than producing uniform outcomes, digital agricultural technologies interact with local institutions and social norms that shape how labour restructuring unfolds in practice. Overall, the findings suggest that digital transformation produces differentiated patterns of labour restructuring whose outcomes depend on governance arrangements, local institutions, and socio-economic context.

Local wisdom as a mechanism of social protection in digital agricultural transformation

The findings demonstrate that the adoption of Agriculture 4.0 technologies is not a purely technical or economically driven process but is deeply shaped by local wisdom, including social norms, community values, and informal governance structures. Rather than passively adopting digital innovations, rural communities actively negotiate technological change in ways that balance productivity with livelihood security. This supports prior research emphasizing that agricultural digitalization is socially embedded and mediated by local institutions (Carolan, 2025; Nelson & Stathers, 2024). In the Indonesian horticultural context, this mediation is clearly reflected in the selective and strategic adoption of digital technologies. Farmers predominantly implement digital tools in post-harvest processing and marketing, such as online platforms and supply chain systems, while maintaining manual labour in cultivation stages. In Cianjur Regency, this selective adoption can be illustrated through the increasing use of digital marketing channels, mobile communication platforms, and cooperative-based coordination mechanisms for product distribution and market access, while labour-intensive cultivation activities such as planting, harvesting, and field maintenance largely remain manual. Farmer groups and local networks often mediate these decisions collectively, reflecting an effort to balance technological modernization with employment preservation and community welfare. This hybrid approach allows productivity improvements without undermining employment. Similar patterns have been observed in smallholder systems, where technologies are adopted incrementally to complement, rather than replace, existing labour structures (Sumberg & Giller, 2022). These findings suggest that local wisdom functions as a form of informal social protection, enabling communities to manage the risks associated with technological disruption. In labour-intensive systems, rapid automation could displace workers; however, community-based decision-making often prioritizes employment stability and social cohesion. As a result, digital tools are introduced in areas that enhance efficiency without threatening core livelihood activities. The role of local wisdom is particularly significant in smallholder agriculture, where production is embedded in social relations and collective practices. Decisions about

technology adoption are evaluated not only in terms of economic returns but also in relation to community welfare, risk, and cultural acceptability. Farmer groups and local institutions play a central role in facilitating knowledge sharing, coordinating adoption, and ensuring that technological change aligns with local priorities.

As summarized in **Table 2**, local wisdom shapes digital transformation through multiple dimensions, including community governance, social norms, livelihood protection, and knowledge integration. These mechanisms collectively promote gradual and adaptive adoption, preventing abrupt labour displacement while supporting incremental innovation. For instance, digital marketing platforms expand market access and create new roles without reducing demand for farm labour, while traditional knowledge continues to guide cultivation practices.

Table 2

Role of local wisdom in mediating digital agricultural transformation

Dimension	Characteristics of Local Wisdom	Impact on Technology Adoption	Labour Implications	References
Community governance	Collective decision-making through farmer groups and local institutions	Technologies adopted based on social acceptance and shared interests	Maintains employment and reduces the risk of labour displacement	Nelson & Stathers, 2024
Social norms and values	Emphasis on community welfare and social stability	Gradual and cautious adoption of digital technologies	Prevents abrupt labour disruption	Carolan, 2025
Livelihood protection	Priority on sustaining rural income and employment	Technologies concentrated in non-labour-displacing activities (e.g., marketing)	Preserves labour demand in cultivation stages	Sumberg & Giller, 2022
Knowledge integration	Combination of traditional knowledge with digital tools	Hybrid farming systems (manual + digital practices)	Sustains the role of human expertise	Nettle et al., 2025
Institutional coordination	Role of cooperatives and farmer networks in knowledge sharing	Facilitates collective learning and controlled diffusion of innovation	Enables skill upgrading without job loss	Prajapati et al., 2025
Market adaptation	Use of digital platforms for marketing and distribution	Adoption driven by market access rather than automation	Creates new roles in digital marketing and logistics	Singh et al., 2022
Risk management	Avoidance of technologies that threaten livelihood security	Selective and staged adoption of innovations	Ensures income and employment stability	Fonchingong Che & Bang, 2024
Social inclusion	Participation across community members in farming systems	Technologies adapted to local labour structures	Supports inclusive employment patterns	Akello & Brunori, 2025
Gender dynamics	Gendered division of labour within agricultural tasks	Digital tools integrated into existing roles (e.g., post-harvest, marketing)	Creates opportunities but may reinforce inequalities	Sikdar & Anand, 2025
Governance integration	Interaction between local institutions and policy frameworks	Local actors reinterpret top-down digital policies	Aligns innovation with rural development needs	Carolan, 2025

This process can be further understood through a multi-level governance perspective, illustrated in **Figure 2**. Digital transformation is influenced by interactions between national policies, institutional actors, and community-level practices. While governments promote rapid technological modernization, local actors reinterpret and adapt these initiatives based on socio-economic realities. Consequently, technological adoption emerges as a negotiated process rather than a uniform transition. In the Cianjur case, this governance dynamic explains why digital technologies are concentrated in specific stages of production. Farmers recognize the benefits of digitalization for improving market efficiency but remain cautious about adopting technologies that could disrupt employment. This reflects a form of adaptive modernization, where innovation is integrated gradually to preserve social stability. Overall, local wisdom functions as a mediating governance mechanism that aligns technological innovation with community priorities and socially sustainable labour outcomes.

Figure 2*Multi-level governance of digital agricultural transformation*

Gendered labour implications of agriculture 4.0

The findings reveal that digital transformation in agriculture has profound but uneven implications for gendered labour relations, reinforcing the view that Agriculture 4.0 is not socially neutral but embedded within existing inequalities (Carolan, 2025; Sikdar & Anand, 2025). In many rural contexts, agricultural work remains structured along gendered lines, with men typically engaged in mechanized and market-oriented activities, while women are concentrated in labour-intensive tasks such as planting, harvesting, and post-harvest processing (Chandel et al., 2025). These divisions shape how technological change is experienced across different groups. The results indicate that digital technologies simultaneously create new opportunities and new risks for women. On one hand, tools such as digital marketing platforms, mobile advisory services, and online marketplaces expand women's access to information and markets. In the Indonesian horticultural context, women are increasingly involved in post-harvest activities and digital marketing, enabling greater participation in value chains and income generation. This aligns with evidence that digital platforms can enhance women's economic agency by reducing dependence on intermediaries and improving market access (Akello & Brunori, 2025). On the other hand, the study highlights the persistence of a digital gender divide. Women often face limited access to smartphones, internet connectivity, financial resources, and technical training, constraining their ability to benefit from digital agriculture. As a result, technological gains tend to be unevenly distributed, favouring those with existing access to resources and capabilities. This supports broader concerns that digital transformation may reproduce or intensify structural inequalities if inclusive policies are not implemented (Carolan, 2025). Interpreted through a feminist political economy lens, these outcomes demonstrate that technological innovation is embedded within pre-existing systems of power, resource inequality, and gendered labour segmentation. Access to digital opportunities therefore depends not only on technology availability but also on institutional inclusion, social norms, and unequal distributions of economic resources. Importantly, the impact of

digitalization varies across the agricultural value chain. Automation is most visible in post-harvest stages, such as sorting, grading, and packaging, where women's labour is highly concentrated. The introduction of automated systems in these areas can reduce demand for manual work, increasing vulnerability among women workers. However, the findings also show that such displacement is not uniform. As discussed in Section 4.2, communities often adopt technologies selectively, which helps preserve employment in labour-intensive activities and mitigate adverse impacts.

This dynamic is reflected in [Table 3](#), which demonstrates that while certain technologies reduce manual labour in female-dominated roles, others generate new opportunities in areas such as digital marketing, information access, and entrepreneurial activities. Thus, digital transformation produces a dual effect, simultaneously enabling empowerment and reinforcing exclusion depending on access and capability.

Table 3
Gendered labour implications of agriculture 4.0 technologies

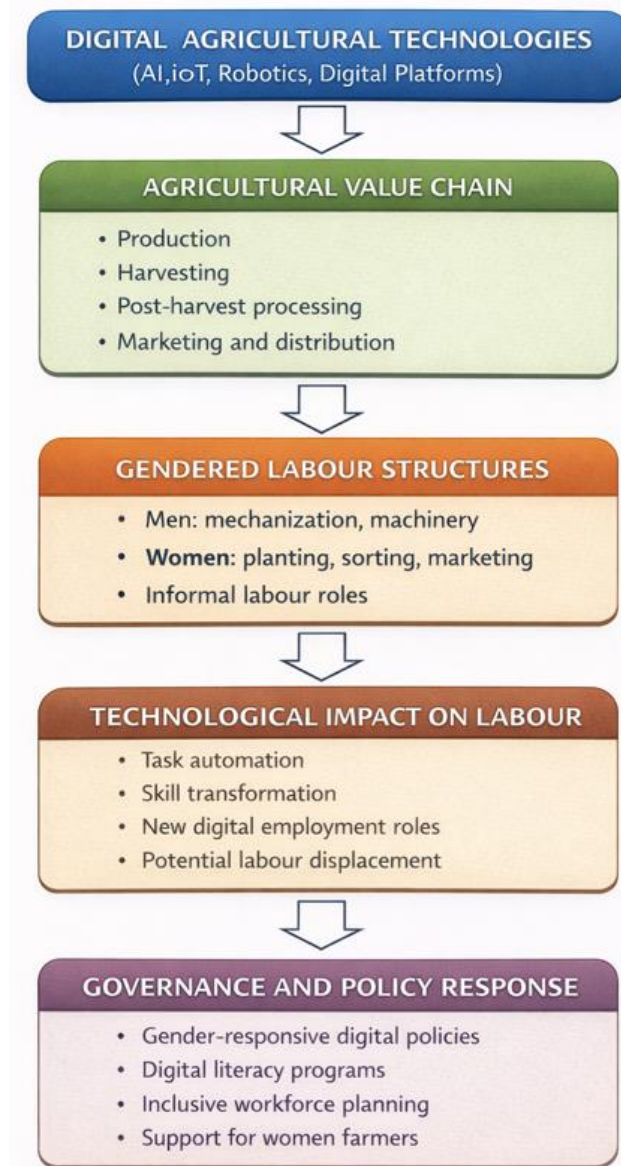
Technology	Stage of Agricultural Value Chain	Gendered Labour Impact	Opportunities for Women	Risks for Women	References
Precision agriculture sensors	Crop monitoring	Reduces manual field inspection (often male-dominated)	Access to farm data and decision support	Requires digital literacy and device access	Aarif et al., 2025
Agricultural drones	Crop monitoring and spraying	Replaces manual pesticide application	Entry into technical and skilled roles	Excludes low-skilled workers	Sarker et al., 2025
AI-based farm analytics	Farm management	Shifts decision-making toward data-driven systems	Participation in digital farm management	Limited access to training and tools	Eze et al., 2025
Smart irrigation systems	Irrigation control	Reduces routine manual irrigation tasks	Involvement in system monitoring	Technical skill requirements	Aarif et al., 2025
Automated sorting and grading	Post-harvest processing	Reduces labour in female-dominated tasks	Supervisory and quality control roles	Job displacement in low-skilled work	Chandel et al., 2025
Digital marketing platforms	Agricultural marketing	Expands market participation beyond physical markets	Enables women entrepreneurship and direct sales	Digital access and literacy gaps	Singh et al., 2022
Mobile advisory platforms	Knowledge dissemination	Improves access to agricultural information	Enhances decision-making capacity	Dependence on digital access	Akello & Brunori, 2025
Digital supply chain systems	Distribution and logistics	Formalizes coordination roles	New roles in logistics and coordination	Exclusion from formal systems	Prajapati et al., 2025
E-commerce platforms	Agricultural trade	Enables direct producer-to-consumer interaction	Expands women's market access	Platform access inequalities	Carolan, 2025
Digital finance platforms	Investment and credit access	Alters financial inclusion pathways	Access to microfinance and digital payments	Unequal access to financial services	Sikdar & Anand, 2025

These interactions are further conceptualized in [Figure 3](#), which illustrates how gendered labour outcomes are shaped by the interplay between technology, governance, and institutional support. The framework emphasizes that digital agriculture does not automatically improve gender equality; rather, outcomes depend on the presence of gender-responsive policies, access to skills, and inclusive governance mechanisms. Overall, the findings suggest that Agriculture 4.0 leads to a restructuring of gendered labour rather than its elimination, with

differentiated impacts across tasks and groups. While digital technologies can open new pathways for women's participation, they also risk displacing workers in traditional roles and reinforcing existing disparities. Ensuring equitable outcomes therefore requires targeted interventions in digital literacy, access to resources, and institutional support for women. From a policy perspective, integrating gender-sensitive workforce planning into digital agriculture strategies is essential. Without deliberate efforts to address structural barriers, technological transformation may deepen inequalities rather than contribute to inclusive rural development.

Figure 3

Gendered labour dynamics in agriculture 4.0



Governance gaps and policy implications for inclusive digital agricultural transformation

The findings indicate that while Agriculture 4.0 offers significant potential for improving productivity, efficiency, and market access, its outcomes are not inherently inclusive. Rather, the impacts of digital transformation are shaped by governance structures, institutional coordination, and policy design. This supports existing research highlighting that digital agriculture is a governance challenge as much as a technological one (Carolan, 2025). A key issue emerging from the study is institutional fragmentation. Digital agricultural transformation requires coordination across agriculture, technology, labour, and education sectors, yet these domains often operate in silos. In the Indonesian context, national policies promote Industry 4.0 adoption, but local implementation remains uneven due to limited coordination between agencies. As a result, technological adoption tends to be incremental and fragmented rather than strategically integrated. This gap limits the ability of digital agriculture to generate broad-based development outcomes. Another major challenge is the rural digital divide, which restricts access to infrastructure, devices, and technical knowledge. Smallholder farmers and rural workers often lack the financial resources and digital literacy required to adopt advanced technologies. This leads

to uneven adoption patterns, where benefits are concentrated among more resourced actors. Consistent with earlier findings, such disparities risk reinforcing existing inequalities within rural labour systems (Hertini & Risdwiyanto, 2025). The study also highlights persistent gender-based governance gaps. Women face structural barriers in access to land, credit, and digital technologies, limiting their participation in digital agricultural systems. Without targeted interventions, digital transformation may reproduce these inequalities rather than alleviate them (Sikdar & Anand, 2025). This reinforces the need for gender-responsive policies that explicitly address access, training, and institutional inclusion. At the same time, the findings emphasize the critical role of local governance and community institutions. Farmer groups and cooperatives act as informal governance mechanisms that mediate technological adoption. In Cianjur, these groups adopt a selective approach, integrating digital tools in ways that enhance productivity while preserving employment. This bottom-up governance model demonstrates how local institutions can balance innovation with social protection, ensuring that technological change aligns with community priorities.

These dynamics are summarized in **Table 4**, which outlines key governance challenges alongside corresponding policy responses. The table shows that effective digital transformation requires coordinated interventions across infrastructure development, skills training, financial support, and inclusive policy design. Importantly, governance responses must go beyond technological provision to address underlying social and institutional constraints.

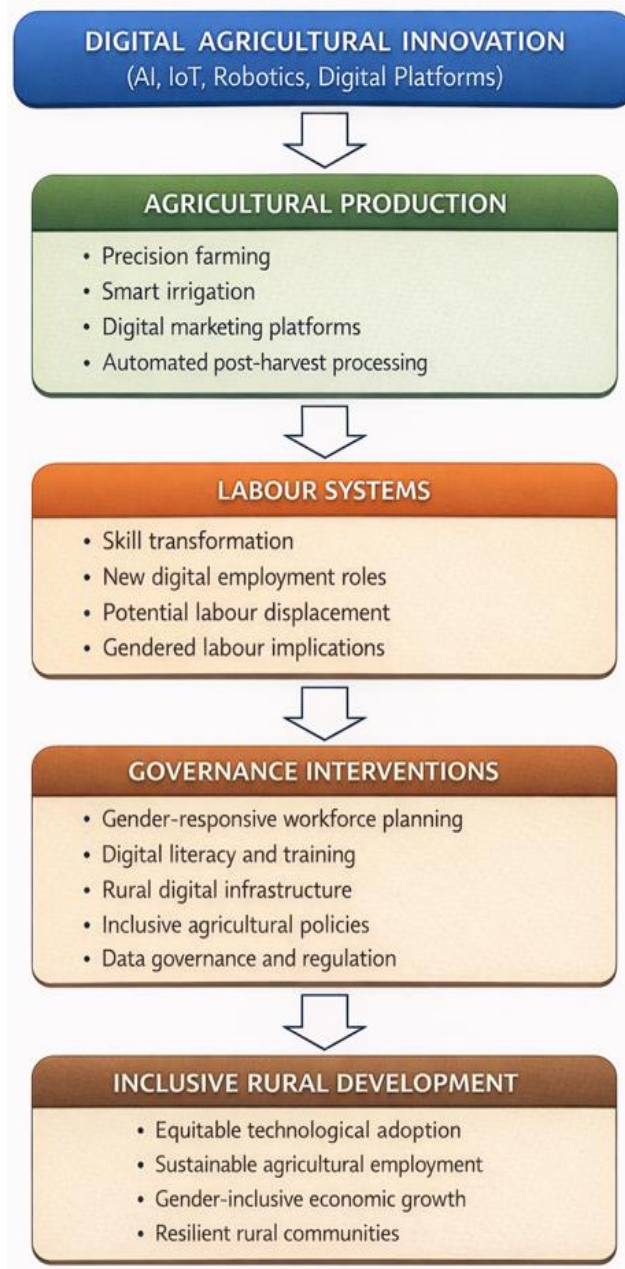
Table 4

Governance challenges and policy responses in digital agricultural transformation

Governance Challenge	Description	Policy Implications	Recommended Interventions	References
Institutional fragmentation	Weak coordination across agriculture, technology, labour, and education sectors	Ineffective and fragmented implementation of digital agriculture strategies	Cross-sector governance frameworks and integrated policy design	Carolan, 2025
Rural digital divide	Unequal access to internet, devices, and digital infrastructure	Exclusion of smallholders from digital transformation	Investment in rural broadband and affordable digital access	Hertini & Risdwiyanto, 2025
Digital skills gap	Limited technical and digital literacy among farmers and workers	Low adoption and inefficient use of technologies	Targeted training, extension services, and capacity-building programs	Nettle et al., 2025
Gender inequality	Women's restricted access to land, finance, and digital tools	Unequal participation in digital agriculture benefits	Gender-responsive policies, training, and access to resources	Sikdar & Anand, 2025
Financial constraints	High costs of digital technologies and limited access to credit	Unequal adoption between large and small farms	Subsidies, microfinance, and support for smallholder investment	Abbasi et al., 2022
Data governance issues	Unclear ownership, control, and use of agricultural data	Risk of power concentration among large firms	Transparent data policies and farmer data rights frameworks	Carolan, 2025
Market access inequalities	Smallholders face barriers in digital markets	Unequal integration into value chains	Support for digital cooperatives and platform inclusion	Singh et al., 2022
Education and training gaps	Limited formal education on digital agriculture technologies	Slow workforce adaptation to technological change	Integration of digital agriculture into education systems	Eze et al., 2025
Infrastructure limitations	Poor rural connectivity and technological support systems	Restricted functionality of digital tools	Expansion of digital infrastructure and technical support services	Aarif et al., 2025
Social inclusion challenges	Vulnerable groups excluded from technological benefits	Reinforcement of rural labour inequalities	Inclusive workforce planning and targeted support programs	Akello & Brunori, 2025

The interaction between these elements is further illustrated in Figure 4, which conceptualizes digital transformation as an outcome of the interplay between technology, labour systems, and governance structures. The framework highlights that inclusive outcomes depend on aligning technological innovation with institutional capacity and social inclusion strategies. These findings reinforce that digital agricultural transformation is fundamentally a multi-level governance process requiring alignment between technological innovation, institutional coordination, and social inclusion. Without integrated and inclusive policy frameworks, digitalization may exacerbate inequalities and marginalize vulnerable groups. Conversely, when supported by coordinated governance, local participation, and gender-sensitive interventions, Agriculture 4.0 can contribute to more equitable and sustainable rural development. From a policy perspective, this underscores the need for integrated, inclusive, and context-sensitive approaches that combine technological advancement with social protection, skills development, and equitable access to resources.

Figure 4
Governance Framework for Inclusive Digital Agricultural Transformation



IMPLICATIONS OF THE STUDY

Theoretical implications

This study contributes to the growing body of scholarship on digital agricultural transformation by integrating perspectives from workforce planning theory, feminist political economy, and governance studies to examine the social implications of Agriculture 4.0. By situating digital agricultural transformation within labour, gender, and governance debates simultaneously, the study provides a more holistic account of how Agriculture 4.0 unfolds within socially embedded rural contexts. While much of the existing literature on digital agriculture focuses primarily on technological innovation, productivity gains, and efficiency improvements, this research highlights the importance of examining technological transformation through a broader socio-political lens that considers labour relations, gender inequality, and community governance. First, the findings extend workforce planning theory by demonstrating that labour outcomes in technologically transforming agricultural systems cannot be fully explained through conventional supply–demand models. Traditional workforce planning frameworks, such as Mondy’s labour demand–supply approach, often assume that technological automation will lead to reductions in labour demand. However, the empirical insights from this study suggest that labour outcomes are mediated by social and institutional factors, including local knowledge systems, cultural norms, and community governance structures. In labour-intensive agricultural systems, technological adoption may therefore lead to labour restructuring rather than labour displacement, producing hybrid production models that combine digital tools with manual labour practices. Second, the study contributes to feminist political economy literature by highlighting how digital agricultural transformation interacts with gendered labour structures within rural economies. Existing research has extensively documented the feminisation of agriculture, yet relatively little attention has been given to how emerging digital technologies reshape these gender dynamics. By examining the intersection of Agriculture 4.0 technologies with gendered labour roles in horticultural agriculture, this study demonstrates that technological innovation can simultaneously create new economic opportunities for women while also reproducing structural inequalities related to access to resources, digital infrastructure, and institutional support. This finding reinforces feminist arguments that technological change is not socially neutral but is embedded within existing power relations that influence who benefits from innovation. Third, this research contributes to emerging scholarship on digital governance in agriculture. The findings highlight the importance of multi-level governance systems in shaping technological adoption and labour outcomes within rural economies. Rather than viewing digital transformation as a purely technological process, the study emphasizes that technological adoption is mediated by interactions between national policy frameworks, institutional actors, and community-level governance structures. This perspective contributes to broader debates on inclusive digital development by demonstrating how local governance institutions, such as farmer groups and cooperatives, play critical roles in adapting technological innovations to local socio-economic conditions.

Practical implications

The findings of this study have several important practical implications for stakeholders involved in agricultural development, including farmers, agricultural organizations, technology providers, and rural development practitioners.

- First, the results highlight the importance of community-based approaches to technological adoption. Rather than promoting rapid automation across all stages of agricultural production, development practitioners and technology providers should recognize the value of hybrid production systems that combine digital tools with traditional labour practices. Such approaches allow rural communities to benefit from technological innovation while preserving employment opportunities and maintaining social stability.
- Second, the study underscores the importance of digital literacy and skills development within rural agricultural communities. As Agriculture 4.0 technologies increasingly require competencies related to data analysis, digital marketing, and technology management, farmers and agricultural workers must develop new skill sets to participate effectively in digital agricultural systems. Training programs, extension services, and community-based learning initiatives can play critical roles in supporting these transitions.
- Third, the findings suggest that digital platforms and online marketplaces offer significant opportunities for expanding market access for small-scale agricultural producers, particularly in sectors such as horticulture. Digital marketing tools can enable farmers to connect directly with consumers, reduce dependence on intermediaries, and increase the value captured within local agricultural value chains. Supporting farmers in adopting digital marketing strategies can therefore contribute to improving rural incomes and strengthening agricultural competitiveness.
- Finally, the study highlights the importance of inclusive technology design. Technology developers should consider the needs and constraints of smallholder farmers and rural labourers when designing digital

agricultural tools. Technologies that are affordable, accessible, and compatible with existing farming practices are more likely to be adopted and sustained within rural communities.

Policy implications

The findings of this study also have significant implications for policymakers seeking to promote inclusive digital agricultural transformation.

- First, governments should prioritize integrated policy frameworks that coordinate efforts across agriculture, labour, technology, and rural development sectors. Digital agricultural transformation involves multiple institutional actors, and effective governance requires collaboration between agencies responsible for agricultural development, digital infrastructure, labour regulation, and education.
- Second, policymakers must address the digital divide in rural areas by investing in digital infrastructure, including reliable internet connectivity and affordable digital devices. Expanding rural broadband networks and supporting community-based digital access initiatives can help ensure that smallholder farmers and rural labourers are able to participate in digital agricultural systems.
- Third, governments should implement gender-responsive agricultural policies to ensure that women benefit from digital agricultural innovation. Practical interventions may include community-based digital literacy workshops specifically designed for women farmers, subsidized access to smartphones and digital advisory tools, mentorship programs for women-led agricultural enterprises, and targeted financing schemes supporting women's participation in digital value chains. Institutional reforms improving women's access to land ownership, agricultural training, and leadership opportunities within farmer organizations are equally important for ensuring equitable participation.
- Fourth, policymakers should promote inclusive workforce planning strategies that anticipate the labour implications of digital agricultural transformation. This may involve developing training programs for emerging digital agricultural roles, supporting transitions for workers displaced by automation, and strengthening labour protections within technologically transforming agricultural sectors.
- Finally, governments should recognize the importance of local governance and community institutions in shaping technological adoption. Policies that support farmer cooperatives, community-based organizations, and local knowledge-sharing networks can help ensure that technological innovations are adapted to local socio-economic conditions and contribute to sustainable rural development.

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

While this study provides valuable insights into the social implications of digital agricultural transformation, several limitations should be acknowledged. First, the study relies primarily on qualitative analysis and secondary data sources. Although this approach allows for a comprehensive examination of institutional and governance dynamics, future research could complement these findings with quantitative empirical studies that measure the labour market impacts of digital agricultural technologies across different agricultural sectors and regions. Second, the research focuses on a specific regional case study within the horticultural agriculture sector. While this context provides rich insights into the interaction between digital technologies and rural labour systems, the findings may not be directly generalizable to all agricultural contexts. Comparative studies across multiple regions and agricultural sectors would help further clarify how technological transformation affects rural labour systems under different institutional and socio-economic conditions. Third, the study primarily examines the governance and labour implications of digital agricultural transformation rather than evaluating the technical performance of specific digital technologies. Future research could adopt interdisciplinary approaches that combine socio-economic analysis with technical assessments of agricultural technologies to better understand how technological design influences labour outcomes and adoption patterns. Future research should also explore the long-term gender implications of digital agricultural transformation, particularly in relation to women's economic empowerment, leadership roles within agricultural cooperatives, and participation in digital agricultural value chains. Longitudinal studies examining how gender roles evolve in response to technological change would provide valuable insights for developing more inclusive agricultural policies. Additionally, scholars may examine the role of platform economies and data governance within digital agriculture. As agricultural production becomes increasingly integrated with digital platforms and data infrastructures, questions related to data ownership, privacy, and digital sovereignty are likely to become increasingly important for rural communities.

CONCLUSION

The digital transformation of agriculture represents a major shift in how agricultural production systems operate, offering new opportunities for improving productivity, sustainability, and market integration. These

findings reinforce the argument that digital agricultural modernization must be evaluated not solely through technological performance indicators but also through its implications for labour equity, gender inclusion, and governance capacity. However, the findings of this study demonstrate that technological innovation alone does not determine the social outcomes of agricultural modernization. Instead, the impacts of Agriculture 4.0 technologies on rural labour systems are shaped by a complex interplay of technological capabilities, governance structures, and community practices. By examining the case of horticultural agriculture in Indonesia, this study shows that rural communities actively negotiate technological transitions through locally embedded practices and governance mechanisms. Rather than fully automating agricultural production, farmers often adopt digital technologies selectively in ways that complement existing labour systems and preserve rural employment. These hybrid production models illustrate how local wisdom and community governance can mediate technological change and mitigate the disruptive effects of automation. At the same time, the research highlights that digital agricultural transformation has important gender implications. While digital technologies can create new opportunities for women's participation in agricultural markets, structural barriers related to access to resources, digital infrastructure, and institutional support continue to limit women's participation in digital agricultural systems. Addressing these inequalities requires gender-responsive policies and inclusive governance frameworks that ensure equitable access to technological innovation. Ultimately, the transition toward Agriculture 4.0 must be understood not only as a technological transformation but also as a social and political process that reshapes labour relations, gender dynamics, and governance structures within rural economies. Policies that integrate technological innovation with social inclusion, gender equality, and community participation will be essential for ensuring that digital agricultural transformation contributes to sustainable and equitable rural development. The study makes three principal contributions. Theoretically, it extends the Agriculture 4.0 scholarship by integrating workforce planning theory, feminist political economy, and governance analysis to explain digital transformation as a socially negotiated rather than purely technological process. Practically, the findings demonstrate the importance of community-based technological adaptation, hybrid labour systems, and gender-sensitive workforce development within agricultural modernization. From a policy perspective, the study highlights the need for integrated governance frameworks, digital literacy initiatives, gender-responsive interventions, and strengthened local institutional participation to ensure that digital agricultural transformation contributes to inclusive and equitable rural development.

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Ethical statement

The article entitled Gendered Labour and Local Wisdom in Digital Agriculture Workforce Planning is derived from the study conducted in accordance with established ethical guidelines for social research. Informed content was obtained from interview participants before data compilation. Participants were informed about the purpose of the research, voluntary participation, confidentiality, and their right to withdraw at any time. Identifying information has been anonymized to protect participants' privacy. Ethical approval was obtained from the Research Agency of the Institute of Home Affairs (Institut Pemerintahan Dalam Negeri).

Competing interests

The authors declare no competing interests.

Author contributions

All authors contributed equally to this study. They were jointly involved in conceptualization and research design, methodology development, data collection and analysis, literature review, theoretical framing, data interpretation, supervision, and the writing, review, and editing of the manuscript.

Data availability

The qualitative interview and observational data supporting the findings of this study are not publicly available due to ethical and confidentiality considerations. Anonymized excerpts and supporting materials may be made available from the corresponding author upon reasonable request.

AI disclosure

AI-assisted tools were used for language editing and clarity improvement during manuscript preparation. All substantive ideas, theoretical framing, analysis, and interpretations are the authors' own. The authors take full responsibility for the content of this article.

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REFERENCES

- Aarif KO, M., Alam, A., & Hotak, Y. (2025). Smart sensor technologies shaping the future of precision agriculture: Recent advances and future outlooks. *Journal of Sensors*, 2025, Article 2460098. <https://doi.org/10.1155/jsen/2460098>
- Abbasi, R., Martinez, P., & Ahmad, R. (2022). The digitization of agricultural industry—a systematic literature review on agriculture 4.0. *Smart Agricultural Technology*, 2, Article 100042. <https://doi.org/10.1016/j.atech.2022.100042>
- Agarwal, P., Swami, S., & Malhotra, S. K. (2024). Artificial intelligence adoption in the post COVID-19 new-normal and role of smart technologies in transforming business: A review. *Journal of Science and Technology Policy Management*, 15(3), 506–529. <https://doi.org/10.1108/JSTPM-08-2021-0122>
- Ahmadi, S., Amendolagine, V., & LaSala, P. (2025). Unpacking the impacts of digitalization of knowledge transfer in agri-food sector, through sociotechnical systems theory: A systematic literature review. *Agricultural and Food Economics*, 13(1), Article 51. <https://doi.org/10.1007/s40953-025-00451-7>

- Aji, A. S. S., & Akbardin, M. (2024). Economic insights into workforce dynamics: Analyzing labor supply, demand, and compensation. *Advances in Human Resource Management Research*, 2(2), 113–126. <https://doi.org/10.59890/ahrm.v2i2.2369>
- Akello, B. C., & Brunori, G. (2025). Leveraging digital solutions to address gender inequalities in EU agriculture: A CODECS framework application. *Open Research Europe*, 5, Article 322. <https://doi.org/10.12688/openreseurope.19546.1>
- Almarashdi, H. S., Abu Khurma, O., AlArabi, K., Abulebdeh, E., & Yousef, J. (2026). AI-enhanced STEM education: A bibliometric study of research trends toward achieving sustainable development goals. *European Journal of STEM Education*, 11(1), Article 16. <https://doi.org/10.20897/ejsteme/18190>
- Andang, Sadat, A., Sapiruddin, Agustinasari, Sudarsana, I. P. E., Ferdiansyah, Syakur, A. A., & Noge, M. D. (2026). Multicultural education in Indonesia: A systematic review and bibliometric analysis. *Journal of Ethnic and Cultural Studies*, 13(3), 80–111. <https://doi.org/10.66815/ejecs/2911>
- Atinaf, M., Anteneh, S., & Kifle, M. (2023). A holistic understanding of information and communication technology for development through context, resilience, and sustainability: Evidence from a local agriculture extension information service in Ethiopia. *The Electronic Journal of Information Systems in Developing Countries*, 89(6), Article e12260. <https://doi.org/10.1002/isd2.12260>
- Carolan, M. (2025). Labor, digital farming, and the politics of affect: Getting closer to the feeling of work, leisure, and distinction in cloud-based countrysides. *Human Geography*, Advance online publication. <https://doi.org/10.1177/19427786251347027>
- Chandel, N. S., Chakraborty, S. K., Jat, D., & Chouhan, P. (2024). Smart farming management system: Pre and post-production interventions. In *Artificial intelligence techniques in smart agriculture* (pp. 67–82). Springer. https://doi.org/10.1007/978-981-97-0341-8_4
- Chandel, P., Sharma, C., Thakur, A., Gupta, N., & Mithu, A. (2025). Challenges and prospects for organic agriculture among women. In *Data mining and information security: Proceedings of ICDMIS 2024* (Vol. 1, p. 393). Springer.
- Coker, D. C. (2026). Building the thematic structure in qualitative research: The theme construction tool. *American Journal of Qualitative Research*, 10(3), 95–125. <https://doi.org/10.66815/ajqr/18485>
- Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. SAGE.
- Dalgaldere, S. (2025). Generative artificial intelligence in crisis journalism: A comparative analysis of ChatGPT and Gemini news texts. *ISophos: International Journal of Information, Technology and Philosophy*, 8(15), 1–11. <https://doi.org/10.20897/isophos/18446>
- de Avila, F. R., & Barbosa, J. L. V. (2025). Smart environments in digital agriculture: A systematic review and taxonomy. *Computers and Electronics in Agriculture*, 236, Article 110393. <https://doi.org/10.1016/j.compag.2025.110393>
- Doss, C. R. (2025). Gender and agricultural productivity. *Annual Review of Resource Economics*, 17. Advance online publication. <https://doi.org/10.1146/annurev-resource-111923-043933>
- Durán, Y., Gómez-Valenzuela, V., & Ramírez, K. (2023). Socio-technical transitions and sustainable agriculture in Latin America and the Caribbean: A systematic review of the literature 2010–2021. *Frontiers in Sustainable Food Systems*, 7, Article 1145263. <https://doi.org/10.3389/fsufs.2023.1145263>
- Elson, D. (2023). Gender equality and inclusive growth. In *The political economy of global manufacturing, business and finance* (pp. 51–70). Springer. https://doi.org/10.1007/978-3-031-44582-1_4
- Eze, V. H. U., Eze, E. C., Alaneme, G. U., Bubu, P. E., Nnadi, E. O. E., & Okon, M. B. (2025). Integrating IoT sensors and machine learning for sustainable precision agroecology: Enhancing crop resilience and resource efficiency through data-driven strategies, challenges, and future prospects. *Discover Agriculture*, 3(1), Article 83. <https://doi.org/10.1007/s44378-025-00083-z>
- Fonchingong Che, C., & Bang, H. N. (2024). Towards a "social justice ecosystem framework" for enhancing livelihoods and sustainability in pastoralist communities. *Societies*, 14(11), Article 239. <https://doi.org/10.3390/soc14110239>
- Fraser, N., Maignushca, B., & Masquelier, C. (2024). Theorising power and resistance under contemporary capitalism: An interview with Nancy Fraser. *European Journal of Social Theory*, 27(4), 645–655. <https://doi.org/10.1177/13684310231221241>
- Gava, R., Cotrim, M. F., Teodoro, L. P. R., Santana, D. C., Ratke, R. F., de Oliveira, I. C., de Cássia Félix Alvarez, R., da Silva Junior, C. A., & Teodoro, P. E. (2025). Less water and less carbon emission: Irrigation strategies reduce soil CO₂ emissions in wheat and triticale cultivars. *Discover Agriculture*, 3(1), Article 277. <https://doi.org/10.1007/s44378-025-00277-3>
- Gupta, A. (2026). Bodies under scanner: AI, surveillance, and gendered resistance in Manjula Padmanabhan's Harvest. *Journal of Interdisciplinary Research in Artificial Intelligence and Society*, 2(1), Article 2. <https://doi.org/10.20897/jirais/18487>

- Hertini, E. S., & Risdiyanto, A. (2025). Industrial Revolution 4.0 and the future of the agricultural sector: A theoretical study on technological adaptation and its impact on farmers' welfare. *Technology and Society Perspectives (TACIT)*, 3(3), 363–372. <https://doi.org/10.61100/tacit.v3i3.235>
- Katz, N. (2026). Digital inequality in context: A socio-technical analysis of Arab students' remote learning in Israel. *Asia Pacific Journal of Education and Society*, 14(1), Article 6. <https://doi.org/10.20897/apjes/17975>
- Levkoe, C., Andrée, P., Ballamingie, P., Tasala, K., Wilson, A., & Korzun, M. (2023). Civil society engagement in food systems governance in Canada: Experiences, gaps, and possibilities. *Journal of Agriculture, Food Systems, and Community Development*, 12(2), 267–286. <https://doi.org/10.5304/jafscd.2023.122.019>
- Mackay, F., Kenny, M., & Chappell, L. (2010). New institutionalism through a gender lens: Towards a feminist institutionalism? *International Political Science Review*, 31(5), 573–588. <https://doi.org/10.1177/0192512110388788>
- Malhotra, C., & Anand, R. (2020). Accelerating public service delivery in India: Application of internet of things and artificial intelligence in agriculture. In *Proceedings of the 13th International Conference on Theory and Practice of Electronic Governance* (pp. 499–502). ACM. <https://doi.org/10.1145/3428502.3428561>
- Mansoor, M. (2021). Citizens' trust in government as a function of good governance and government agency's provision of quality information on social media during COVID-19. *Government Information Quarterly*, 38(4), Article 101597. <https://doi.org/10.1016/j.giq.2021.101597>
- Manzoor, F., Wei, L., Siraj, M., Lu, X., & Qiyang, G. (2025). Digital agriculture technology adoption in low and middle-income countries—a review of contemporary literature. *Frontiers in Sustainable Food Systems*, 9, Article 1621851. <https://doi.org/10.3389/fsufs.2025.1621851>
- Mugion, R. G., Ungaro, V., Pietro, L. D., Amin, A., & Bisceglia, F. (2026). Mapping women's role in agriculture 4.0: A bibliometric analysis and conceptual framework. *Agriculture*, 16(2), Article 214. <https://doi.org/10.3390/agriculture16020214>
- Nettle, R., Ayre, M., Reichelt, N., Santhanam-Martin, M., & Vikas, A. (2025). Farm transformation in the context of climate change: Beyond the incremental-transformational divide. *Journal of Rural Studies*, 116, Article 103628. <https://doi.org/10.1016/j.jrurstud.2025.103628>
- Noor, U., Mansoor, M., & Rabbani, S. (2021). Brand hate and retaliation in Muslim consumers: Does offensive advertising matter? *Journal of Islamic Marketing*, 13(6), 1395–1413. <https://doi.org/10.1108/JIMA-10-2019-0215>
- Ossome, L. (2025). Gender and development in the agrarian south. *World Development*, 188, Article 106876. <https://doi.org/10.1016/j.worlddev.2024.106876>
- Prajapati, C. S., Priya, N. K., Bishnoi, S., Vishwakarma, S. K., Buvanewari, K., Shastri, S., Tripathi, S., & Jadhav, A. (2025). The role of participatory approaches in modern agricultural extension: Bridging knowledge gaps for sustainable farming practices. *Journal of Experimental Agriculture International*, 47(2), 204–222. <https://doi.org/10.9734/jeai/2025/v47i22512>
- Ronzhin, A., Figurek, A., Surovtsev, V., & Dibirova, K. (2025). Digital transformation and precision farming as catalysts of rural development. *Land*, 14(7), Article 1464. <https://doi.org/10.3390/land14071464>
- Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., LeBlanc, J., Martin, R., Neufeld, H. T., & Nixon, A. (2019). Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. *Journal of Rural Studies*, 68, 112–122. <https://doi.org/10.1016/j.jrurstud.2019.01.023>
- Rulandari, N., & Silalahi, A. D. K. (2025). Achieving effectiveness of public service in AI-enabled service from public value theory: Does human–AI collaboration matter? *Transforming Government: People, Process and Policy*, 19(2), 428–452. <https://doi.org/10.1108/TG-09-2024-0158>
- Sarker, M. R., Abdolrasol, M. G., Mohamad Hanif Md, S., Kadir, R. A., Ahmad, M. N., & Olazagoitia, J. L. (2025). Advancing agriculture automation systems: Technological innovations, possible applications, challenges, and recommendations. *Advances in Agriculture*, 2025, Article 5518653. <https://doi.org/10.1155/adva/5518653>
- Schaefer, M., Schmitt Olabisi, L., Arola, K., Poitra, C. M., Matz, E., Seigel, M., Schelly, C., Adesanya, A., & Bessette, D. (2021). Understanding socio-technological systems change through an indigenous community-based participatory framework. *Sustainability*, 13(4), Article 2257. <https://doi.org/10.3390/su13042257>
- Shen, Z., Wang, S., Boussemart, J.-P., & Hao, Y. (2022). Digital transition and green growth in Chinese agriculture. *Technological Forecasting and Social Change*, 181, Article 121742. <https://doi.org/10.1016/j.techfore.2022.121742>
- Shrestha, P., Bhandari, G., Rai, M., Khadka, N., Rai, S., Tamrakar, S., Khanal, A., & Giri, S. (2024). Promoting decent work and equal pay in the informal agricultural sector: A gender perspective. *Journal of Sustainability and Environmental Management*, 3(2), 111–120. <https://doi.org/10.3126/jsem.v3i2.73025>

- Sikdar, S., & Anand, B. (2025). Empowerment of farm women in the context of sustainable development: Illustrations on challenges and plausible innovative solutions. In *Women empowerment in agriculture: A pathway towards sustainable development* (p. 90). Apple Academic Press.
- Singh, R., Singh, R., Gehlot, A., Akram, S. V., Priyadarshi, N., & Twala, B. (2022). Horticulture 4.0: Adoption of industry 4.0 technologies in horticulture for meeting sustainable farming. *Applied Sciences*, 12(24), Article 12557. <https://doi.org/10.3390/app122412557>
- Sultana, F. (2017). Gender and water in a changing climate: Challenges and opportunities. In C. Fröhlich, G. Gioli, R. Cremades, & H. Myrntinen (Eds.), *Water security across the gender divide* (pp. 17–33). Springer. https://doi.org/10.1007/978-3-319-64046-4_2
- Sumberg, J., & Giller, K. E. (2022). What is 'conventional' agriculture? *Global Food Security*, 32, Article 100617. <https://doi.org/10.1016/j.gfs.2022.100617>
- Tripura, E., & Rakhi, M. S. (2026). Advancing women's empowerment in Bangladesh through social safety nets: Prospects and challenges. *Feminist Encounters: A Journal of Critical Studies in Culture and Politics*, 10(2), Article 2. <https://doi.org/10.20897/femenc/18269>
- Webb, R. (2026). Post pandemic English language teacher development: A global perspective. *European Journal of Education & Language Review*, 2(1), Article 1. <https://doi.org/10.20897/ejelt/17719>
- Zheng, Y. H., Shi, G., Zhong, H., Liu, M. T., & Lin, Z. (2023). Motivating strategic front-line employees for innovative sales in the digital transformation era: The mediating role of salesperson learning. *Technological Forecasting and Social Change*, 193, Article 122593. <https://doi.org/10.1016/j.techfore.2023.122593>