frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 11 February 2026
DOI 10.3389/fsufs.2026.1655881

OPEN ACCESS

EDITED BY
Raj Raj,
Dr. B. R. Ambedkar National Institute of Technology Jalandhar, India

REVIEWED BY
Diana Surová,
Czech University of Life Sciences Prague, Czechia
Shifadjzic Khan,
Kyungpook National University, Republic of Korea

*CORRESPONDENCE
Audrone Ispiryan
✉ audrone.ispiryan@vdu.lt

RECEIVED 28 June 2025
REVISED 03 January 2026
ACCEPTED 20 January 2026
PUBLISHED 11 February 2026

CITATION
Sermuksnyte-Alesiuniene K and Ispiryan A (2026) The impact of digital technology on sustainable agriculture and bioeconomy. *Front. Sustain. Food Syst.* 10:1655881. doi: 10.3389/fsufs.2026.1655881

The impact of digital technology on sustainable agriculture and bioeconomy

Kristina Sermuksnyte-Alesiuniene[1] and Audrone Ispiryan[2]*

[1]Lithuanian Centre for Social Sciences, Institute of Economics and Rural Development, Vilnius, Lithuania, [2]Vytautas Magnus University, Agriculture Academy, Bioeconomy Research Institute, Akademija, Lithuania

Introduction: The study addresses the critical challenge of uneven digital technology adoption and its varied impact on sustainability in the agricultural sector globally. It investigates how digital technologies can be leveraged to enhance key sustainability metrics, including renewable energy integration and resource efficiency, within the bioeconomy framework. Focusing on the integration of digital tools and their efficacy in enhancing key sustainability metrics, this study aim to provide insights into how digital innovations can bolster sustainable agricultural practices across diverse environmental, regulatory, and socio-economic landscapes.

Methods: A mixed-methods research design was employed, combining quantitative analysis of sustainability indicators with qualitative assessment of regional socio-economic and infrastructural conditions. Empirical data were collected from multiple international regions and aggregated at the regional level. Correlation analysis and multivariable ordinary least squares regression models were applied to examine the relationship between digital technology adoption and sustainability outcomes, controlling for policy support, infrastructure availability, and economic context. Sensitivity analysis was conducted by systematically varying input parameters to assess the robustness of model results.

Results and discussion: Study results show that areas exhibiting elevated rates of technological adoption, including Europe and North America, exhibit significant advancements in sustainability metrics, such as enhanced integration of renewable energy sources and improved resource efficiency. In contrast, Asia and Africa exhibit modest improvements, which highlights the critical need for region-specific strategies to overcome infrastructural and adoption barriers. This study develops a model that quantifies the relationship between digital technology adoption and sustainability improvements across different agricultural contexts. Findings highlight the need for promoting technological parity to achieve holistic agricultural sustainability and leverage digital technologies for climate resilience, food security, and renewable energy use in agriculture.

KEYWORDS

agri-tech adoption, circular bioeconomy, digital technologies, global agriculture, sustainability metrics

1 Introduction

The integration of digital technologies with sustainable agricultural methodologies is significantly transforming the global agricultural landscape, driven by the urgent need to address challenges like climate change, food security, and the ecological impacts of traditional farming. However, the effectiveness of these technologies in promoting sustainability varies widely across different regions, influenced by numerous contextual factors. Moreover, the lack of a comprehensive framework to assess their impact limits their broader adoption and effectiveness. This necessitates a thorough evaluation that includes regional socio-economic, environmental, and policy dimensions to clarify digital technologies' role in advancing sustainable agricultural practices, marking a major paradigm shift in how agricultural methods are developed and applied (Rennings et al., 2023; Golembiewski et al., 2015).

The bioeconomy is defined here as a sector of the economy that produces renewable raw materials (biomass) and processes these raw materials and waste of biological origin into products with added value. It provides a conceptual framework that integrates sustainable biomass production and conversion into consumables, bio commodities and bioenergy and has become a critical model for addressing pressing global issues such as climate change, food security and resource management (Mccormick and Kautto, 2013; Gawel et al., 2019; Diakosavvas and Frezal, 2019; Bell et al., 2018). Digital technologies are being integrated into agricultural systems at an unprecedented speed, ranging from big data analysis to remote monitoring and artificial intelligence, which fundamentally alters traditional agricultural methodologies (TWI2050, 2020; Knell, 2021; Gebresenbet et al., 2023; Sharma et al., 2022; Mana et al., 2024).

The bioeconomy encompasses economic activities based on the sustainable use of biological resources (Rojas-Serrano et al., 2024; Befort, 2020; Bugge et al., 2016; Egea et al., 2021; European Commission, 2022; European Environment Agency, 2018; Tan and Lamers, 2021) and circular resource flows (von Braun, 2020; Watanabe et al., 2018; Zeverte-Rivza et al., 2023; Mboli et al., 2022; Fielke et al., 2020), integrating biomass production and renewable resource conversion with innovative technologies (Fielke et al., 2020; Goller et al., 2021; Liobikiene et al., 2021; Tsegaye et al., 2021; Zabaniotou, 2018). Together, these trends are driving a new wave of innovation aimed at enhancing sustainability in agriculture, a critical sector that sits at the heart of the agricultural bioeconomic model (Prakasa Rao et al., 2021; Bhagat et al., 2022). Incorporating the concepts of digital sustainability and sustainable agriculture, this paper aims to systematically evaluate the role of digital tools in promoting sustainable agricultural outcomes across various global regions. Sustainability in this context is defined as the capacity to maintain agricultural productivity, environmental health, and socio-economic well-being over time, ensuring that current needs are met without compromising the ability of future generations to meet their own requirements (Rosati et al., 2024). Digital sustainability, in turn, is described as the application of digital technologies to monitor, evaluate, and enhance sustainability metrics, promoting data-driven strategies to optimize the efficiency and effectiveness of sustainable practices (Giuliani and Baron, 2023).

In this research, sustainability is assessed through measurable indicators, including reductions in greenhouse gas emissions, improvements in water use efficiency, increases in carbon sequestration, and the share of renewable energy in farm operations. Digital technology adoption is quantified using a composite index that reflects adoption rate, cost accessibility, and integration of digital tools into agricultural management systems. These concepts guide the analysis throughout the paper, providing a structured lens through which the impact of digital tools is assessed.

The Common Agricultural Policy (CAP) of the European Union constitutes a pivotal instrument for fostering sustainable agricultural transformation through the integration of digital innovation, environmental objectives, and targeted policy support (Pe'er et al., 2020; Abiri et al., 2023). Within this framework, digitalization is promoted as a mechanism to enhance efficiency, transparency, and evidence-based decision-making in agricultural management. Policy frameworks of this kind increasingly depend on territorial data integration to monitor patterns of technological adoption, assess regional disparities, and inform adaptive governance strategies. In this study, the CAP serves as an analytical reference point for examining how policy-driven digitalization can advance sustainability objectives within the broader context of agricultural bioeconomy development.

Sustainability within the domain of agriculture encompasses the judicious utilization of natural resources (Obaisi et al., 2022) to fulfill present food production requirements without jeopardizing the capacity of subsequent generations to satisfy their own requirements (United Nations, 1987). This endeavor necessitates a comprehensive methodology that accounts for environmental, economic, and social dimensions (Chkarat et al., 2023; McCampbell et al., 2023; Muhie, 2022; Kamakaula, 2024; Hariram et al., 2023). Digital technologies present unparalleled opportunities to progress sustainability objectives by furnishing accurate, real-time data that can enhance decision-making processes (Kim and Kim, 2022), optimize the utilization of resources (Peng et al., 2023), and ultimately diminish the environmental impact of agricultural practices (Wang et al., 2024; Balasundram et al., 2023). The implementation of sensors and Internet of Things (IoT) devices enables the systematic observation of soil moisture content, crop health and nutrient levels, allowing farmers to administer inputs with enhanced precision. These advancements aid in the sustainable advancement of land management methodologies (Rajak et al., 2023; Karuna et al., 2024; Islam et al., 2023; Choubey et al., 2024). Bioeconomy necessitates the formulation and utilization of comprehensive sustainability indicators. Such indicators are essential for evaluating the repercussions of agricultural practices on the environment. Digital technologies provide essential data for assessing the environmental, economic, and social dimensions of agricultural sustainability. Their integration with quantifiable indicators enhances analytical precision, comparability, and policy relevance, marking a substantive advancement in the development of data-informed approaches within the agricultural bioeconomy (Wei et al., 2022; Barañano et al., 2021; Frisvold et al., 2021; Trigo et al., 2023; Dönmez et al., 2024; Wijerathna-Yapa and Pathirana, 2022; Wang and Mei, 2024). Although digital technologies are often portrayed as unequivocal enablers of sustainability, empirical evidence suggests a more nuanced reality. Several studies indicate that digitalization does not automatically lead to improved sustainability outcomes and may, in some contexts, generate mixed or even adverse effects. High investment and maintenance costs, limited digital literacy, unequal access to infrastructure, and data ownership concerns can constrain benefits or exacerbate existing inequalities, particularly among smallholder farmers and in low-income regions. In some cases, efficiency gains from digital tools may also increase resource use through rebound effects, offsetting environmental improvements. These findings highlight the importance of contextual conditions in shaping the sustainability impacts of digital technologies. Although previous research has explored how digital technologies are used in agriculture, many of these studies have focused on specific regions or individual tools, without offering broader comparisons or using consistent measures of sustainability. Often, they don't provide solid empirical evidence linking the use of digital tools to actual improvements in sustainability, in areas with different levels of infrastructure and economic development. This study aims to fill those gaps by developing a data-driven, comparative framework that connects digital technology adoption with measurable sustainability improvements across a range of global contexts.

The objective of this investigation is to assess the efficacy of digital sustainability metrics in augmenting agricultural sustainability across various global regions, emphasizing their ability to incorporate sophisticated digital technologies for the enhancement of decision-making processes, the optimization of resource utilization, and the reduction of environmental repercussions within the context of the bioeconomy paradigm.

2 Research methods

This research utilizes a mixed-methods approach to evaluate the effectiveness of digital instruments in promoting agricultural sustainability across distinct global locales. Methodological framework incorporates empirical data acquisition, quantitative evaluations, and qualitative analyses, facilitating a comprehensive investigation of the influence of digital technologies within the agricultural domain. The methodology applied and delineated in the subsequent Table 1 is in close alignment with the principles of quantitative research as articulated by Creswell (2002) and Kumar (2018).

2.1 Data sources and collection

The research undertakes a comparative analysis of tool adoption across Europe, America, Asia, and Africa, elucidating regional discrepancies and potential strategies for improving accessibility. A non-probability purposive sampling strategy was applied in this study. Respondents were selected based on their direct involvement in agricultural production, advisory services, or policy-related activities relevant to digital agriculture. To increase regional diversity and representation, snowball sampling was additionally employed, particularly in regions with limited access to formal farmer registries and digital communication channels. While this approach does not allow for full statistical generalization, it is appropriate for exploratory cross-regional analysis and aligns with the mixed-methods design of the study. Data were compiled from multiple international sources, including the Food and Agriculture Organization (FAO), International Energy Agency (IEA), World Bank. The literature search was conducted as a structured keyword-based review using the databases MDPI (mdpi.com), ResearchGate (researchgate.net), Elsevier (sciencedirect.co), and Springer (springerlink.com). The search combined thematic and methodological terms to capture studies addressing the intersection of digitalization and sustainability in agriculture. The main keywords included combinations such as *"digital agriculture," "agricultural bioeconomy," "sustainable farming," "digital transformation," "precision agriculture," "renewable energy in agriculture,"* and *"data-driven sustainability."* Boolean operators (AND, OR) were used to refine the search results, and the selection focused on publications from 2010 onwards to reflect the period of accelerated digital adoption in agriculture. In total, 186 records were retrieved through the database search, and following the screening of titles and abstracts, 94 studies meeting the inclusion criteria were retained for detailed content analysis.

Secondary datasets were complemented by a structured survey conducted between March and July 2023, covering 290 respondents (r.) across Europe (82 r.), the Americas (81 r.), Asia (70 r.), and Africa (57 r.). To ensure clarity regarding the study's geographical scope, all countries included in the survey sample are listed with respondent counts in Supplementary material 1, and all regional references in the analysis are explicitly qualified as referring only to the countries represented in this sample. Respondents included farmers, agronomists, and policymakers, providing diverse perspectives on digital adoption and sustainability outcomes. To improve coverage in areas with limited internet access, both online and telephone modes were employed, minimizing sampling bias. Out of 290 respondents, approximately 200 (∼69%) were farmers, 60 (∼21%) were agronomists or researchers, and 30 (∼10%) were policymakers. The role of the survey responses is primarily descriptive and corroborative. We did not treat each survey respondent as an independent observation in the main regressions. Instead, survey results were aggregated and used to construct indices or to validate patterns observed in secondary data.

The questionnaire was organized into four thematic sections. (1) Digital tool usage: respondents identified the types of digital tools they use and reported the frequency of use in their operations. (2) Perceived sustainability impacts: questions probed how these tools affect sustainability outcomes, whether farmers observed improvements in resource efficiency, enhanced crop yields or quality, or other environmental benefits attributable to digital tool adoption. (3) Barriers to adoption: the survey asked about challenges limiting wider use of digital tools, including financial barriers, infrastructural issues, and human-capacity factors. (4) Policy and institutional support: finally, respondents were asked about external support mechanisms like awareness of government programs, extension services, or corporate initiatives providing training, subsidies, or technical support for digital agriculture, and how these influence their adoption decisions. To enhance transparency, key aggregate findings were summarized from this survey as part of the methods. The full survey questionnaire is provided in the Supplementary material 1.

2.2 Variable definition and categorization

Sustainability was operationalized through four core quantitative indicators: (i) carbon sequestration (t CO_2/ha):

TABLE 1 Utilization of tools and strategies for sustainable agriculture across continents (2021/2022).

Category	Europe	Asia	America	Africa
Organic farming	10.5% of agricultural land (16.9 Mha)	~2.3% of agricultural land (~8.2 Mha)	0.5% of agricultural land (~3.6 Mha)	~1.1% of agricultural land (~2.7 Mha)
Leading countries	Austria (26.1%), Estonia (22.4%), Sweden (20.4%)	India (2.8 million ha), China (2.3 million ha)	Argentina (3.6 million ha), USA (2.3 million ha)	Ethiopia (332,000 ha), Tanzania (287,000 ha)
Agri-environmental measures (AEM)	17% of agricultural area	Limited data, varying adoption	10% of agricultural area (North America)	Limited adoption, mostly in pilot stages
Precision agriculture	25–30% adoption rate	5–10% adoption rate	20–25% adoption rate (higher in the US)	<5% adoption rate
Integrated pest management	70–80% adoption rate	40–50% adoption rate	60–70% adoption rate	30–40% adoption rate
Sustainable soil management	45% of arable land	30–35% of arable land	35–40% of arable land	25–30% of arable land
Renewable energy use	>5% of farms with solar/wind installations	<5% of farms with solar/wind installations	7–10% of farms (higher in the US and Brazil)	<3% of farms with solar/wind installations
Water management	25% of irrigated land with advanced techniques	15–20% of irrigated land with advanced techniques	20–25% of irrigated land	10–15% of irrigated land with advanced techniques
Agroforestry	3.6% of agricultural land	2–3% of agricultural land	2–3% of agricultural land	5–7% of agricultural land
Circular agriculture	>50% of agricultural waste recycled	20–25% of agricultural waste recycled	30–35% of agricultural waste recycled	15–20% of agricultural waste recycled
Government and support	Strong CAP, Green Deal, Farm to Fork Strategy	Varying support, increasing in countries like India	Varies, strong in the US and Brazil	Limited, growing support in East and Southern Africa

Data collection and analysis: data were collected from national agricultural statistics databases, environmental impact reports, and direct surveys with farming operations. Statistical analyses included correlation and regression models to understand the influence of governmental support and technological infrastructure on adoption rates.
Sources: Detailed references for data sources and methodologies are provided in references 75–80.

atmospheric carbon stored in soil and biomass; (ii) water use efficiency (kg/m^3): ratio of yield to water use; (iii) greenhouse gas emission reduction (CO_2e): measured via life-cycle assessment data; (iv) renewable energy share (%): proportion of total farm energy derived from renewable sources.

Digital technology adoption was evaluated through a composite index combining adoption rate, cost accessibility (free, freemium, paid), and integration level within farm management. Data were categorized into low (<40%), moderate (40–70%), and high (>70%) adoption rates to enable comparative regional analysis.

Archival data were aggregated from credible and esteemed sources, including the (Word Bank Group, 2023), the (International Energy Agency, 2023), the (Food and Agriculture Organization, n.d.), as well as additional environmental (EBSCO Information Services, 2023; CABI, 2023; Proquest Natural Sciences Database, 2023; Glogal Environmental Database, 2023; Environmental Impact Statement Database, 2023) and economic (AMECO Database, 2023; Fiscal Governance Database, 2023; World Economic Outlook Database, 2023; Organisation for Economic Co-operation and Development, 2023; Kuhlman and Farrington, 2010; EUROSTAT, n.d.; Circularity Gap Report, n.d.; Marcet Research Intellect, n.d.; STATISTA, n.d.a,n; FIBL, n.d.; Food and Agriculture Organization of the United Nations, 2023; Climate FieldView, n.d.; Circular Economy Coalition, n.d.; Crop X, n.d.; Trimble Agriculture Solutions, n.d.; TWI2050, 2019) repositories. Baseline values for each sustainability metric were estimated based on data from approximately 2010, a time period before the widespread adoption of digital tools in sustainability practices. These values represent the performance of each metric without significant digital intervention.

Baseline values for each sustainability metric were established using data from 2010, representing the pre-digital adoption phase in most agricultural systems. Current values were obtained for 2023, providing a temporal comparison that highlights long-term trends and the influence of digital and non-digital factors on sustainability outcomes.

Improvement (%) for each metric was calculated using the following formula:

$$\text{Improvement (\%)} = \frac{\text{Baseline Value (2010)} - \text{Current Value (2023)}}{\text{Baseline Value (2010)}} \times 100$$

This formula calculates the percentage improvement in each sustainability metric, indicating the impact of various interventions, including digital tools. This calculation also provides the percentage increase or decrease in each sustainability metric over the period.

2.3 Analytical procedures

The multi-variable regression models include several control variables to account for structural and contextual differences across regions. Specifically, the models control for (i) policy support intensity, (ii) infrastructure availability (proxied by rural internet access and energy infrastructure indicators), and (iii) economic context. These controls allow for a more accurate isolation of the effect of digital technology adoption on sustainability outcomes.

A stepwise analytical design was applied: (i) literature review and variable identification; (ii) data normalization and aggregation by region; (iii) correlation and regression analyses to determine relationships between digital adoption and sustainability indicators.

The correlation between adoption rates and sustainability outcomes was evaluated using a 1–10 ordinal scale, where higher scores denote stronger associations. This semi-quantitative scale integrates quantitative improvements and contextual qualitative assessment. Multi-variable regression controlled for confounding factors such as policy support and infrastructure, isolating the effect of digital adoption.

According to Ahmadi-Gh Ahmadi-Gh and Bello-Pintado (2022), higher adoption rates generally correlate with stronger sustainability outcomes and effectively implementing sustainability practices improves sustainability outcomes, which then enhances manufacturing firms' competitive ad-vantage, highlights the benefits of sustainability. This is also proven by research conducted by other scientists such as Neves et al. (2022); Cary et al. (2001), or Piñeiro et al. (2020). Some researchers highland that significant improvements in key metrics suggest a higher correlation (Hauser and Katz, 1998; Hong et al., 2006; Varga et al., 2006; Manheim, 2023). Consideration of regional factors, such as infrastructure development, government policies, and socioeconomic conditions, which could influence the effectiveness of digital tools was approved in studies conducted by several scientists in recent years (Katz and Koutroumpis, 2013; Nambisan et al., 2019; Plekhanov et al., 2023; Du et al., 2022; Akimov and Akimova, 2023; Alojail and Khan, 2023).

The correlation score was derived from a combination of quantitative analysis (improvement percentage) and qualitative assessment (regional context and additional influencing factors) and sensitivity analysis was conducted to ensure that the assigned correlation scores are robust. This involved varying the input data (e.g., changing the adoption rates by ±10%) and observing the impact on the improvement percentages and correlation scores. This step helped in validating the reliability of the correlation estimation. The sensitivity analysis was conducted by systematically varying the digital adoption index values by ±10% and ±20% to assess the stability of estimated correlations and regression coefficients. The resulting changes in sustainability improvement percentages remained within a ±5% margin for Europe and North America and within ±8–10% for Asia and Africa, indicating moderate to high robustness of the model outcomes. No reversal in the direction of relationships was observed under these variations, suggesting that the main findings are not highly sensitive to reasonable fluctuations in input assumptions.

For the quantitative analysis, correlation analysis and multi-variable regression modeling were employed to examine the relationship between digital tool adoption and improvements in sustainability metrics. We employed an OLS multi-variable regression model of the form: Sustainability Improvement = $\beta 0 + \beta 1$(Digital Adoption) + β_2^*(Policy Support) + $\beta 3^*$(Infrastructure) + $\beta 4^*$(Economic context) + … + ε. Here, 'Policy Support' was represented by an ordinal score reflecting the strength of digital-agriculture initiatives. 'Infrastructure' was proxied by rural broadband access rates and energy availability, and 'Economic context' by GDP per capita and related socioeconomic indicators. This allowed us to control for structural differences across regions. The regression models controlled for potential confounding factors such as policy support, infrastructure availability, and economic context, to better isolate the effect of digital adoption. All regression results were evaluated for statistical significance using a significance level of $\alpha = 0.05$. In other words, we only considered an observed relationship to be meaningful if there was less than a 5% probability that it occurred by chance. Key outcomes of the regression analysis are reported with their *p*-values in the results section to indicate their significance. This rigorous assessment ensures that the correlations and trends we report are statistically robust and not artifacts of random variation.

All regression analyses were performed using ordinary least squares to explore the relationship between digital adoption and sustainability outcomes, controlling for regional differences. The full outputs of the regression models, including coefficients, confidence intervals, and *p*-values, are provided in Supplementary material 2, along with model fit statistics and the reference category used for categorical variables.

2.4 Validation procedures

To ensure the reliability of the results, several validation steps were applied. Data entries and calculations were independently cross-checked to minimize transcription errors and ensure internal consistency. Key trends were also compared with external sources, including FAO and World Bank data, confirming that observed sustainability improvements between 2010 and 2023 align with established global patterns.

Model robustness was further tested through sensitivity analysis by adjusting the digital adoption index by ±10% (and ±20% in selected cases). These variations resulted in only minor changes in sustainability improvement rates (around 5% in Europe and North America and up to 10% in Asia and Africa) and did not affect the direction or significance of the relationships. The composite score linking digital adoption and sustainability outcomes was constructed using equal weighting of correlation strength, improvement magnitude, and contextual factors, preventing any single dimension from dominating the assessment. All statistical results were evaluated at a 5% significance level ($\alpha = 0.05$). Together, these checks indicate that the framework is robust and that the reported relationships are not driven by data or modeling artifacts.

2.5 Bias management

Potential sampling and data-related biases were addressed through several mitigation measures. A purposive, regionally diverse sampling strategy, complemented by snowball recruitment, was used to capture a wide range of agricultural contexts.

To reduce access-related bias, data collection combined online surveys with telephone interviews in areas with limited internet connectivity, improving inclusion of remote and under-resourced respondents. Regional balance was maintained by ensuring comparable representation from Europe, the Americas, Asia, and Africa. As the sampling was non-probabilistic, findings are interpreted as exploratory rather than fully generalizable.

All responses underwent systematic data cleaning and consistency checks. Records with substantial missing or contradictory information were excluded from quantitative analysis, while minor omissions were handled through pairwise deletion. Statistical imputation was not applied, as sufficient complete cases were available. To limit response and interviewer bias, participation was anonymous and interviewers followed standardized, neutral questioning protocols.

3 Results

The establishment and validation of the digital sustainability framework confirm that a structured, data-driven integration of digital adoption indicators with sustainability metrics can significantly improve agricultural outcomes. The framework connects four key sustainability indicators: carbon sequestration, greenhouse gas emission reduction, water use efficiency, and renewable energy share with measures of digital adoption, including adoption rate, cost accessibility, and technological integration (Kalluri, 2023; Martínez-Peláez et al., 2023; Piacentini and Della Ceca, 2017). The economic and social impact assessment shows persuasive evidence that integrating digital tools in agriculture is not only ecologically beneficial but also economically feasible (Papadopoulos et al., 2024; MacPherson et al., 2022; Fabiani et al., 2020; Birner et al., 2021). The ability of these tools to bridge the disparity between smallholder and large-scale farmers is particularly significant. By making advanced technology accessible to all, these tools can help reduce inequality within the agricultural sector (Papadopoulos et al., 2024; MacPherson et al., 2022; Fabiani et al., 2020; Birner et al., 2021).

Moreover, the integration of gas within the green taxonomy underscores its pivotal function in reconciling immediate sustainability ambitions with long-term decarbonization targets. In numerous regions, particularly in rural locales characterized by limited access to sophisticated renewable technologies, biogas emerges as a pragmatic and scalable solution for fulfilling energy requirements while being congruent with sustainability tenets. This ensures that circular bioeconomy models remain inclusive and responsive to a variety of socio-economic and geographical conditions (Trendov et al., 2019; Rolandi et al., 2021; Slavova and Barrett, 2011; Qi and You, 2024).

The anticipated resilience to climate change represents another critical advantage, as it implies that these instruments could significantly assist agricultural communities in adapting to fluctuating environmental conditions. Below is a comparative table illustrating the application of tools and strategies for sustainable agriculture across various continents: Europe, Asia, America, and Africa. The statistics presented are based on the most recent available data:

Research consistently shows that Europe leads in organic farming, which aligns with the findings that a significant percentage of land in Europe is dedicated to organic practices. Studies by the Research Institute of Organic Agriculture (FiBL) highlight that Europe not only has the highest proportion of organic farmland but also the most developed markets for organic products (FiBL, n.d.). In contrast, Asia and Africa are noted to be lagging, although countries like India and China are making strides in organic farming, as supported by various studies indicating growth in organic certification and consumer demand in these regions.

The structured implementation of AEM in Europe is corroborated by research from the European Commission, which illustrates how EU policies have effectively integrated environmental considerations into agricultural practices. This contrasts sharply with findings from other continents, particularly Africa, where AEM practices are often in pilot stages or adopted inconsistently, as noted in studies by the Food and Agriculture Organization (FAO). The higher adoption rates of renewable energy in North America compared to Africa aligns with findings from the World Bank, which indicate that while North America is leveraging renewable technologies, Africa faces challenges such as infrastructure and investment gaps.

The trend of recycling agricultural waste in Europe, followed by America, is well-documented in various sustainability reports (Teagasc, n.d.; European Commision, n.d.; Asian Agri, n.d.; Golden Agri-Resources Ltd, n.d.). Research indicates that while Asia and Africa are making gradual improvements, they still lag behind, emphasizing the need for policy support and innovation in waste management practices.

Emerging Technologies Precision agriculture adoption increasing, with 25–30% of farms utilizing drones and sensors 15–20% of farms implementing data analytics for crop management 10–15% of farms using AI for yield prediction 5–10% of farms exploring blockchain for supply chain transparency. Emerging trends in sustainable practices show a shift toward regenerative agriculture, with 10–15% of farms adopting cover cropping and agroforestry techniques. Additionally, there is a rising interest in organic farming, with approximately 8–12% of farms transitioning to certified organic practices, reflecting a broader consumer demand for sustainable food sources. Moreover, governmental programs and private sector investments are significantly contributing to the enhancement of accessibility to these technologies, thereby enabling smallholder farmers to reap the benefits of innovations in agricultural methodologies.

The formulation and validation of the digital sustainability framework elicits apprehensions regarding the excessive dependence on digital instruments, which may not necessarily culminate in enhanced sustainability outcomes. Although participatory design workshops are underscored as advantageous, there exists a potential risk that these may inadequately encapsulate the diverse viewpoints of all stakeholders, thereby resulting in a framework that neglects to address the requirements of marginalized groups within the agricultural domain. The prioritization of user engagement, while significant, may inadvertently divert focus from systemic challenges that necessitate more than mere technological adoption to achieve authentic sustainability.

The concept of continuous feedback mechanisms may be overly idealistic, given that they can be resource-demanding and may not produce actionable insights. Dependence on data-driven modifications could inadvertently foster a preoccupation with metrics at the expense of substantive change, thereby undermining the overarching objectives of sustainability. While it is imperative to monitor the effects on environmental and economic metrics, this practice may engender pressure to favor short-term advantages over enduring ecological well-being.

Collaboration with local communities, despite its advantages, may not invariably translate into effective ownership and accountability. In certain instances, external interventions have the potential to disrupt traditional practices, leading to a reliance on digital solutions rather than promoting authentic community-driven initiatives. The assumption that digital instruments possess the capability to successfully mitigate the disparities between smallholder and large-scale agricultural producers' neglects to recognize the deeply rooted structural inequities that continue to exist within the agricultural domain, wherein the allocation of resources and technological advancements remains unevenly distributed.

The assessment of economic and social impacts may present a unidimensional perspective, accentuating the advantages of digital tools without sufficiently addressing potential drawbacks, such as job displacement resulting from automation or the risk of exacerbating existing inequalities. Although the creation of jobs and enhancement of market dynamics are referenced, the ramifications of these transitions on smallholder farmers and rural communities necessitate a more nuanced scrutiny. The comparative table illustrating the application of tools and strategies for sustainable agriculture across various continents may inadvertently simplify intricate regional dynamics. The statistics provided could obscure significant disparities within nations and fail to adequately capture the challenges confronted by farmers in less developed regions. The reliance on broad classifications may neglect local innovations and practices that are not incorporated within the data.

Additionally, the optimistic forecasts regarding resilience to climate change may fail to consider the unpredictable nature of environmental alterations and the limitations of technology in addressing these pressing challenges. The claim that digital instruments can significantly enhance sustainability outcomes must be approached with circumspection, acknowledging that technology in isolation cannot resolve the multifaceted dilemmas associated with climate change and agricultural sustainability. A more integrative approach that amalgamates traditional practices, communal knowledge, and sustainable land management strategies is imperative for the realization of long-term sustainability in agriculture.

Results show that various sustainability practices are implemented across different continents, each utilizing distinct methods to meet environmental, economic, and social sustainability guidelines. In Europe, there is significant integration of renewable energy sources and efforts in carbon sequestration within the agricultural and forestry sectors, as well as high rates of waste recycling and sustainable biomass use. Asia is noted for its growth in bio-based product manufacturing and efforts to improve land use efficiency and biodiversity conservation. America has experienced considerable growth in renewable energy capacities, particularly in wind, solar, and bioenergy sectors, and is actively implementing bio-based circular economy initiatives. Africa is focusing on expanding local bio-based industries and increasing access to renewable energy in rural areas, with emerging initiatives in carbon farming and biodiversity protection, demonstrating a proactive approach to sustainability despite various challenges. These findings highlight the regional approaches to implementing sustainability practices, reflecting their unique priorities and developmental contexts.

The empirical evidence concerning sustainability metrics aimed at propelling the bioeconomy across various continents elucidates unique patterns and avenues for growth, especially when juxtaposed with the prevailing literature in this domain. The preeminence of Europe within bio-based industries is congruent with insights from other scholarly works, notably those produced by the European Commission, which accentuate the economic ramifications of bio-based sectors within the European Union. Conversely, investigations centered on the African continent, such as those conducted by the African Development Bank, underscore the region's potential for establishing indigenous bio-based industries, thereby indicating an urgency for strategic investments and policy frameworks to capitalize on this potential. Nonetheless, while the burgeoning capacity for wind and solar energy in Asia is acknowledged, it remains imperative to address the obstacles to rural energy accessibility in Africa, as delineated in analyses by the World Bank. This underscores a pivotal area for intervention aimed at improving energy equity.

The revelations pertaining to Europe's sustainable biomass methodologies are in harmony with the reports disseminated by the Global Bioenergy Partnership, which stress the significance of sustainable sourcing practices. Investigations originating from Asia similarly indicate a growing inclination toward sustainable methodologies; however, the necessity for Africa to bolster its biomass utilization is in line with scholarly works advocating for integrated resource management paradigms. The focus on land productivity prevalent in Europe and Asia is consistent with research conducted by the Food and Agriculture Organization (FAO), which champions sustainable land management practices.

The enhancements observed in biodiversity indices within Europe resonate with findings from ecological research, while the difficulties encountered by Asia and Africa in advancing biodiversity-friendly practices are thoroughly documented in literature promoting sustainable land utilization. In a similar vein, the necessity for improved water governance in these regions is accentuated in hydrological studies that elucidate the inefficiencies inherent in current irrigation systems. The focus on innovation and investment in research related to bioeconomy technologies is aligned with studies advocating for augmented funding and support for research and development in developing regions, thereby highlighting a crucial area requiring policy attention. The elevated employment rates within bio-based sectors in Europe, in comparison to the latent potential in Asia and Africa, are substantiated by labor market research. The existing literature on sustainable finance underscores the imperative for enhanced investment in green initiatives, particularly in developing regions, to foster job creation and stimulate economic growth.

These findings from the sustainability metrics for the bioeconomy reflect a comprehensive understanding of current trends and challenges across continents. They align with existing research while highlighting significant opportunities for growth, particularly in Asia and Africa. The comparative analysis underscores the need for targeted interventions, policy frameworks, and international cooperation to foster a more sustainable and equitable bioeconomy globally. Engaging local communities and stakeholders in these initiatives is imperative to guarantee that the advantages of sustainable practices are distributed equitably and implemented with efficacy. This collaborative methodology not only augments the effectiveness of projects but also empowers communities to assume proprietorship of their development, resulting in more resilient and adaptive systems. The application of technology and innovation can assume a crucial role in confronting local challenges, facilitating communities to utilize their resources with greater efficiency and sustainability. Fostering education and capacity-building initiatives will equip individuals with the necessary skills to participate actively in the bioeconomy, ensuring that they are not only beneficiaries but also contributors to a thriving ecosystem. This holistic strategy will ultimately create a more inclusive framework, where diverse voices are heard and valued, paving the way for sustainable growth that benefits all stakeholders involved. By prioritizing collaboration and partnerships, we can further enhance the impact of these initiatives, creating synergies that amplify efforts and drive meaningful change across various sectors.

North America demonstrates a high level of digital technology adoption in agriculture, accompanied by notable improvements in sustainability metrics. In the United States and Canada, the widespread use of precision agriculture technologies including farm management software, Internet of Things (IoT) sensors, and data analytics platforms has contributed to significant gains in resource-use efficiency, crop yields, and carbon management. This region benefits from advanced digital infrastructure and consistent investment in agricultural innovation, supporting the strong correlation observed between digital tool adoption and sustainability outcomes. These include increased use of renewable energy on farms, the implementation of efficient irrigation systems, and measurable reductions in greenhouse gas emissions. North America reports high adoption of precision irrigation technologies, contributing to substantial water savings and energy efficiency improvements. The region's performance serves as a benchmark for the effective integration of digital tools into sustainable agricultural practices.

In contrast, South America has made considerable progress in promoting sustainable agriculture and advancing bioeconomy initiatives, though with more moderate and uneven levels of digital adoption. Countries such as Brazil and Argentina lead regional uptake of specific technologies, including satellite-based remote sensing, automated farm machinery, and climate-smart practices. These advancements have supported improvements in crop productivity and the initiation of renewable energy projects in some areas. However, structural barriers continue to constrain broader adoption. As a result, while sustainability indicators such as resource efficiency and agricultural waste recycling have improved in several countries, the overall impact of digital tools remains less consistent compared to North America or Europe. According to study findings, South America's digital adoption rate correlates with moderate gains in renewable energy integration and yield enhancement, but these improvements are more variable and region-dependent. Despite these challenges, South America is actively pursuing circular bioeconomy strategies and exhibits strong potential in bio-based energy production. Realizing this potential will require expanded investment in digital infrastructure and tailored policy frameworks to support widespread and equitable adoption of digital innovations across the region.

Europe emphasizes advanced metrics like bio-based product share, circular economy practices, and carbon sequestration, reflecting its leadership in sustainable practices. Asia focuses on the rapid growth of bioeconomy-related industries, renewable energy, and efficient land use, reflecting the region's industrial scale and diversity. America highlights innovation, renewable energy, and emissions reduction, with a strong emphasis on market-driven growth and environmental sustainability. Africa prioritizes foundational metrics like access to renewable energy, sustainable land use, and local job creation, essential for building a robust bioeconomy in developing contexts.

Table 2 provides a classification of representative digital tools in sustainable agriculture by their primary function and cost category. The selected examples illustrate a range of globally relevant technologies from farm management software to precision automation highlighting how digital tools support sustainable farming practices such as efficient resource use and climate-smart decision-making. All listed tools are pertinent to sustainability objectives, enabling improvements in productivity or resource efficiency while varying widely in affordability and complexity.

TABLE 2 Representative digital agriculture tools categorized by function and cost.

Tool	Primary function	Cost category
CropX—IoT soil monitoring platform	Monitoring and sensing (soil moisture for irrigation)	Moderate-cost (hardware + subscription)
Climate FieldView—data analytics suite	Decision support (in-field monitoring and agronomic analysis)	Moderate-cost (subscription-based)
Trimble Ag—precision ag system	Automation (GPS guidance and farm machinery control)	High-cost (specialized equipment)
FarmLogs—farm management app	Decision support (field recordkeeping and alerts)	Free/low-cost (basic version)
AgriWebb—livestock management software	Decision support (grazing and herd data management)	Moderate-cost (subscription SaaS)
farmOS—open-source platform	Decision support (open-source farm planning and records)	Free/low-cost (open-source, no license fee)
Twiga Foods—mobile marketplace	Market access and logistics (connects farmers to buyers)	Free/low-cost (to farmers, platform-funded)

The cost and functional category of a tool strongly influence its adoption across different regions and farm types. High-cost precision automation systems (e.g. GPS-guided equipment) are predominantly adopted by large, capital-intensive farms in developed regions, where the necessary investment and technical capacity are available. In contrast, smallholder farmers and resource-limited regions gravitate toward free or low-cost tools that fulfill immediate needs like farm management or market access via mobile platforms. Indeed, small farms are more likely to implement affordable decision-support apps designed for ease of use, whereas they often forgo expensive sensor networks or robotics that, despite sustainability benefits, remain impractical without subsidies or infrastructure support. Thus, both cost and functionality shape the diffusion of agri-tech: tools aligning with farmers' economic means and addressing pressing local needs tend to see broader and faster uptake, while those requiring high upfront investment or sophisticated machinery are confined to well-resourced contexts, widening the digital divide in agriculture.

Secondary datasets were complemented by a structured survey implemented between March and July 2023, comprising 290 respondents distributed across Europe (82), the Americas (81), Asia (70), and Africa (57). This distribution ensured balanced regional coverage and enhanced the robustness of comparative analysis. Figure 1 presents the correlation between digital technology adoption and sustainability indicators across regions. The visualization illustrates the strength and direction of associations identified in the dataset. This visual representation helps to quantify the impact of digital technology integration on agricultural practices, providing a clear comparison of how effectively these tools have been utilized in Europe, Asia, America, and Africa to achieve sustainable agriculture goals.

Evaluating the interrelation between the utilization of digital instruments and enhancements in sustainability outcomes across various continents necessitates an analysis of how the embracement of these instruments affects critical sustainability indicators, such as renewable energy incorporation, water utilization efficiency, carbon sequestration, among others.

Europe exhibits a substantial adoption rate of digital instruments, particularly in domains such as precision agriculture, renewable energy governance, and circular economic practices. Instruments such as Power BI, SAP Business One, and Climate Field View are prevalently utilized by enterprises across diverse scales. Sustainability Outcomes: The extensive deployment of digital instruments has markedly facilitated advancements in sustainability outcomes throughout Europe. For example, digital instruments have streamlined energy efficiency, augmented the precision of carbon accounting, and improved resource management within the agricultural and manufacturing sectors. Key Metrics Impacted: Carbon sequestration, renewable energy incorporation, and circular economic practices have demonstrated significant enhancements attributable to the digital innovations and monitoring functionalities afforded by these instruments. Asia presents a heterogeneous adoption rate of digital instruments, with a pronounced prevalence in industrialized regions (e.g., Japan, South Korea) and diminished adoption in rural and developing locales. Instruments like SWAT+ for water management and Simapro for lifecycle assessment are gaining momentum yet remain insufficiently adopted on a universal scale.

In locales where digital instruments are employed, one can observe a discernible enhancement in water utilization efficiency, waste management, and sustainable biomass application. Nonetheless, in less developed regions, the impact is constrained due to diminished adoption rates and inadequate infrastructure. Water utilization efficiency and waste-to-energy conversion have improved in contexts where digital instruments are integrated into management protocols, particularly within the industrial and agricultural domains. America, with a particular emphasis on North America, demonstrate elevated adoption rates of digital instruments across multiple sectors, ranging from agriculture to energy.

The implementation of digital instruments has resulted in marked reductions in greenhouse gas emissions, enhanced land utilization efficiency, and amplified investments in bio-based innovations. Digital platforms have facilitated superior tracking, reporting, and optimization of sustainability endeavors. The reduction of greenhouse gas emissions and advancements in bioeconomy sectors have been particularly shaped by digital instruments, culminating in improved environmental results and a more efficient allocation of resources. The African continent exhibits lower rates of digital tool adoption, primarily attributable to economic limitations, inadequate infrastructure, and restricted access to technology across various regions. In geographical areas where digital technologies have been integrated, there exist improvements in the efficiency of water utilization, the incorporation of sustainable energy solutions, and the creation of job prospects. The overall effectiveness is constrained by the sluggish pace of technology acceptance and the necessity for expansive capacity-building initiatives. Employment within the bioeconomy and water use efficiency have experienced some favorable trends in contexts where digital tools are accessible, particularly in pilot programs and targeted interventions.

High correlation was found in Europe and America. In these regions, the substantial adoption of digital tools exhibits a strong correlation with enhanced sustainability outcomes. Digital tools furnish improved data analytics, optimization, and monitoring capabilities, resulting in more efficient resource utilization, diminished environmental impacts, and expedited advancement toward sustainability objectives. Research results show moderate correlation in Asia. The correlation is moderate owing to inconsistent adoption rates. In areas where digital tools are implemented, notable improvements are evident; however, the overall effect is mitigated by regions characterized by low technology penetration. Finaly, low to moderate correlation was observed in Africa. The correlation is comparatively lower in Africa due to restricted access to digital tools and technologies. However, regions where digital tools are employed exhibit promising enhancements, indicating that an increase in digital adoption could substantially elevate sustainability outcomes. The implementation of the CAP has played a significant role in driving the adoption of digital tools and sustainable practices in Europe. Through targeted subsidies and incentive schemes, the CAP has supported the integration of precision agriculture technologies, agri-environmental measures (AEM), and renewable energy

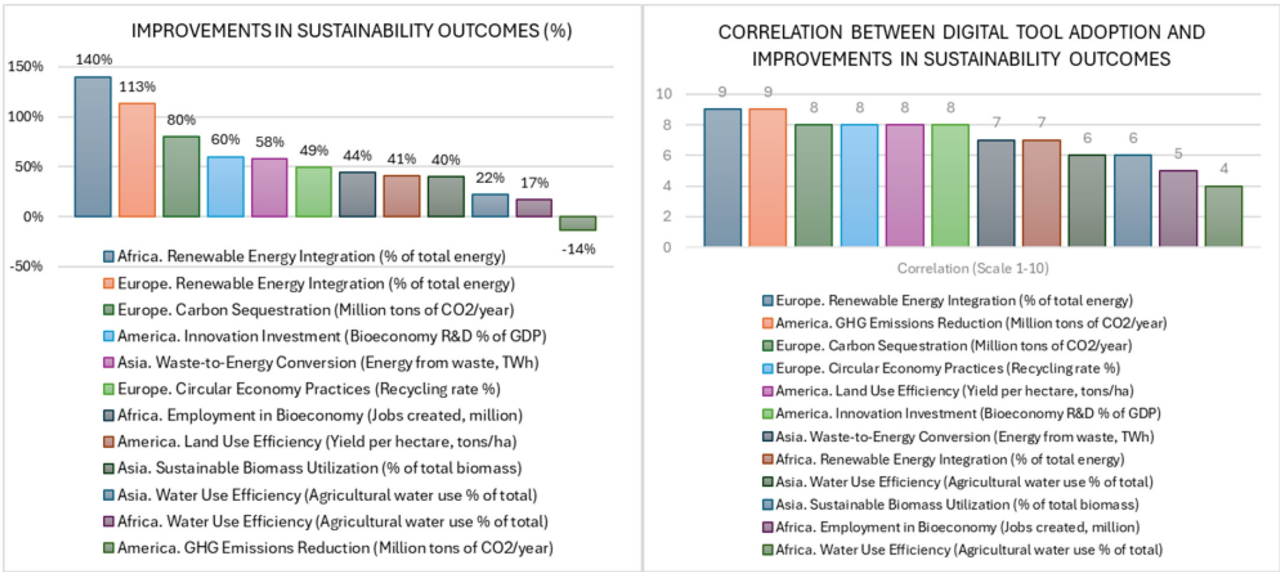

FIGURE 1
Correlation between digital tool adoption and improvements in sustainability outcomes across continents (between 2010 and 2022).

solutions across EU member states. These policy interventions have not only facilitated higher adoption rates but have also contributed to notable improvements in key sustainability metrics, such as carbon sequestration and water use efficiency. As a result, Europe serves as a leading example of how comprehensive policy frameworks can accelerate the uptake of digital innovations in agriculture, promoting both environmental sustainability and economic viability.

While digital tools are recognized as transformative enablers of sustainability, they operate within a complex ecosystem of drivers that collectively influence sustainability outcomes. Between 2010 and 2022, significant advancements in policy frameworks, market dynamics, and technological innovations contributed to observed improvements in key sustainability metrics. Policies such as the EU Green Deal and renewable energy incentives in regions like Europe and North America have accelerated renewable energy adoption and circular economy practices. Simultaneously, increasing consumer demand for sustainable products and corporate commitments to reduce carbon footprints have incentivized innovations across sectors, creating an environment conducive to the uptake of digital tools.

An estimated percentage reflecting the extent of digital tool adoption in sustainability-related sectors across each continent. Selected sustainability indicators that are influenced by digital tools in each continent. Baseline Value (Without Digital Tools): Approximate metric values around the year 2010, prior to the widespread integration of digital tools. Current Value (With Digital Tools): Approximate current values around 2023, encapsulating the effects of digital tools. Improvement (%): Percentage enhancement in each metric, illustrating the efficacy of digital tools.

Figure 1 presents the correlation patterns between digital adoption and sustainability outcomes, illustrating the relative strength and direction of associations across regions rather than implying causality. The 1–10 correlation scale used in this visualization represents a standardized measure of association strength. Each score was derived from three equally weighted components: the quantitative correlation coefficient between adoption rate and sustainability metrics, the magnitude of improvement from baseline to current values, and qualitative contextual evaluation of policy and infrastructural conditions. This approach provides a balanced interpretation of both numerical and contextual dimensions of digital adoption and sustainability linkages.

High digital tool adoption correlates with significant improvements in renewable energy, carbon sequestration, and circular economy practices in Europe. Moderate adoption has led to noticeable, though uneven, improvements in water use efficiency and biomass utilization in Asia. Strong correlation between digital tool adoption and reduced GHG emissions, improved land use efficiency, and increased R&D investment in America. Lower adoption rates, but where tools are used, there have been notable improvements in renewable energy integration and job creation in the bioeconomy in Africa.

This investigation's results are congruent with previous studies that assert digital technologies can markedly improve sustainability outcomes in agriculture, particularly in areas characterized by elevated adoption rates. For example, akin to the investigations conducted by Abiri et al. and Karunathilake et al., which underscore the efficacy of digital instruments such as precision agriculture and Internet of Things (IoT) technologies in enhancing resource management, our findings indicate that Europe and America, regions where these technologies are extensively implemented, demonstrate significant advancements in carbon sequestration and the integration of renewable energy sources (Karunathilake et al., 2023; Mao, 2023).

Nevertheless, while the prevailing literature frequently accentuates the advantages of digital adoption, this study offers a more nuanced analysis by evaluating these advantages across a spectrum of regions. Asia and Africa, for instance, exhibit moderate to low correlations between the utilization of digital tools and sustainability improvements, a finding that stands in contrast to observations made in Europe and North America. This divergence implies that, as elucidated by the research conducted by Mao and Kaboré, infrastructural deficiencies and policy inadequacies profoundly influence the efficacy of digital tools in lower-income regions (Kaboré et al., 2022; TWI2050, 2020). In opposition to existing research that predominantly concentrates on technological repercussions in developed areas, this inquiry emphasizes the necessity of region-specific strategies, particularly in locales with diminished digital infrastructure. These findings resonate with the recommendations posited by TWI2050 (The World in 2050) report, which endorse the implementation of targeted policies and capacity-building initiatives to mitigate digital divides, thereby facilitating the adoption of digital technologies and enhancing sustainability outcomes on a global scale (Ahmetoglu et al., 2022).

The results obtained in this investigation also substantiate earlier work regarding the beneficial influence of digital technologies on the advancement of agricultural sustainability, consistent with the findings of Ahmetoglu et al. and Soori et al., who have illustrated that digital instruments such as the Internet of Things (IoT) and data analytics facilitate more accurate resource management and augment productivity in areas characterized by elevated adoption rates, including Europe and North America (Soori et al., 2024; Qiu et al., 2023). This study, however, extends this understanding by providing a comparative framework across regions, revealing how digital adoption correlates differently with sustainability outcomes depending on regional economic and infrastructural conditions.

This work also highlights that, unlike findings by Qiu et al. and Díaz-Arancibia et al., which often underscore broad benefits of digital adoption, regions such as Africa experience limited gains, largely due to socio-economic barriers and lower adoption rates (Díaz-Arancibia et al., 2024; Pereira et al., 2022). This perspective supports the conclusions of Muhie and other scholars advocating for capacity-building and financial support in digital adoption to maximize these tools' sustainability impacts in low-income regions?.

In line with Pereira et al., this study also notes the rising importance of categorizing digital tools by cost and accessibility, a crucial factor for improving sustainability in small-scale agriculture, especially in Asia and Africa where affordability remains a barrier. By categorizing tools according to region and farm size, the study offers a practical approach to addressing disparities and enabling more inclusive access to sustainable digital solutions. The presented figures exemplify the beneficial influence that digital instruments exert on the promotion of sustainability objectives across various continents, exhibiting disparate levels of effectiveness contingent upon the region's digital infrastructure and the extent of technology adoption. The association between the utilization of digital tools and sustainability results is most pronounced in regions characterized by elevated technological adoption (such as Europe and North America), while it is less robust in regions where digital infrastructure remains underdeveloped (notably Asia and Africa). Augmenting access to digital tools, particularly in the contexts of Asia and Africa, possesses the potential to significantly improve global sustainability outcomes.

Based on the previously acquired data and in accordance with the specified objectives of the research, a comprehensive model has been constructed and illustrated in Figure 2 below. According to this model, correlation coefficients should be calculated for each pair of variables to assess the extent of the relationship between the dependent variables (sustainability outcomes) and the independent variables. A sensitivity analysis can be performed to assess the robustness of the influence of each factor by manipulating key antecedents and observing the resulting differences in sustainability outcomes. This methodological framework facilitates the factors that have the greatest and most persistent impact on sustainability.

To validate the findings, we examined the statistical significance of the regression results. The overall regression model showed a highly significant fit (overall F-test, $p < 0.01$), indicating that the included variables collectively explain a substantial portion of the variance in sustainability outcomes. Importantly, the regression coefficient for digital tool adoption was positive and statistically significant for Europe and North America ($p < 0.01$), confirming a strong association between higher adoption rates and improved sustainability metrics in these regions. In Asia, the effect was more moderate but still significant ($p < 0.05$). In contrast, for Africa the adoption coefficient did not reach statistical significance at the 5% level ($p > 0.05$), reflecting higher variability and the influence of other factors in that region. These significance results underscore that the observed strong correlations in Europe and North America are unlikely due to chance, whereas the weaker correlation noted in Africa should be interpreted with caution.

This model provides a thorough examination of how variations in each predictor affect sustainability outcomes, thus assisting in the identification of the most effective strategies for enhancing the role of digital adoption in sustainable agriculture. By employing the Sensitivity Analysis and Correlation Model as outlined, the study's data can be methodically analyzed to quantify the relationships between these determinants and sustainability outcomes. This model allows for the creation of tailored strategies that respond to the unique needs of each region. In areas with low digital adoption rates, the model can reveal which factors whether related to policy support or infrastructure development would most effectively boost adoption and enhance sustainability outcomes.

The paradigm of circular bioeconomy models is fundamentally anchored in the objective of reducing reliance on non-renewable resources through the enhancement of renewable biological materials utilization and the incorporation of sustainability principles within production systems. Such models transcend conventional circular economy paradigms by accentuating the regeneration and optimal utilization of bio-based resources, including biomass, bioenergy, and organic waste. A significant progression within this domain is the incorporation of renewable gases, such as biogas and biomethane, into the green taxonomy. This integration aligns with the sustainability objectives articulated by the EU by advocating for cleaner energy alternatives derived from organic waste, agricultural by-products, and other bio-based

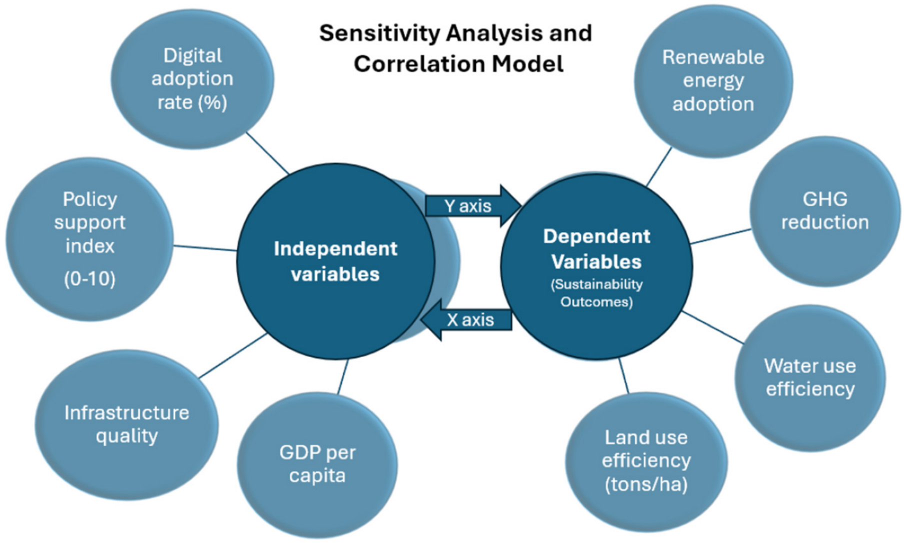

FIGURE 2
Sensitivity analysis and correlation model.

materials, thereby effectively closing resource loops and mitigating greenhouse gas emissions.

Study findings both align with and extend those of similar studies conducted by McCampbell et al. or Wang et al. in various regions, underscoring the global relevance of this research. The study in Rwanda revealed that smallholder farmers had "*limited capacity to access and use phone-based extension services, especially those requiring a smartphone*", highlighting a clear "*need for capacity building*" to improve digital tool adoption (McCampbell et al., 2021). This mirrors observation that inadequate digital infrastructure and skills can impede sustainability gains in developing regions. Similarly, in China, recent analyses indicate that the expansion of the digital economy significantly lowers agricultural carbon emission intensity, though with heterogeneous impacts across different provinces (Wang and Mei, 2024). Such parallels situate results within a global narrative, high digital adoption tends to drive sustainability improvements, whereas low adoption correlates with modest outcomes, a pattern evident from Africa to Asia. These comparisons not only validate core findings but also highlight the originality of multi-region approach, which captures cross-regional disparities that single-country studies might overlook. By situating the study in this wider context, we underline its practical relevance namely, the importance of tailoring digital agriculture strategies to specific regional conditions, as one size does not fit all in enhancing sustainability.

Nevertheless, this study is not without limitations, and acknowledging these factors is crucial for scientific rigor. First, there is a possibility of biases in this analysis. For example, in the selection of case study locales or the sustainability indicators used, which might influence the outcomes. Data, drawn from various international sources and time frames, also come with constraints; differences in data quality and availability between regions may have affected the depth of comparisons. Additionally, the reliance on aggregated regional indicators and a correlational research design means that causal relationships cannot be definitively established. The broad scope of this study, while a strength, also implies that generalizability to any specific country or local context should be done with caution, local socio-economic and environmental nuances can differ markedly from the regional trends we identified. Despite these caveats, transparently discussing these limitations strengthens the validity of conclusions. It delineates the bounds of analysis and points to areas for future inquiry (such as more granular, country-specific studies and longitudinal analyses) to build upon findings.

Theoretically, the empirical findings substantiate the digital transformation theory within the agricultural sector, which asserts that the process of technology adoption is influenced not solely by infrastructural components but also by institutional, economic, and behavioral determinants. Cross-regional analysis elucidates the uneven distribution of technology adoption, which is attributable to structural inequities. Thereby corroborating frameworks that prioritize socio-technical systems over a strictly technological determinism. From a policy standpoint, the outcomes underscore the necessity for specific, targeted interventions aimed at bridging the digital divide, with particular emphasis on the contexts of Asia and Africa. These interventions encompass the enhancement of rural broadband and energy infrastructure, the provision of subsidies for fundamental digital tools for smallholder farmers, the incorporation of digital literacy into agricultural extension programs, and the promotion of public-private partnerships to facilitate the development of regionally tailored technologies. Policy incentives, including tax relief for agricultural technology startups, microfinancing options for farmers investing in digital resources, and the establishment of data-sharing platforms for local cooperatives, could significantly improve both the affordability and accessibility of these technologies. These pragmatic strategies harmonize digital innovation with inclusive sustainability objectives and present actionable pathways for large-scale implementation.

By reinforcing the nexus between bioeconomy and energy transitions, circular bioeconomy models unveil a distinctive opportunity to combat climate change, bolster energy security, and enhance economic resilience. Nonetheless, the successful implementation of these models necessitates a comprehensive policy framework that incentivizes renewable gas production, facilitates infrastructure enhancement, and assures market accessibility. Such initiatives can cultivate a robust ecosystem that integrates bio-based resources, renewable energy, and sustainability objectives within a cohesive green taxonomy framework.

An important limitation of this study is the aggregation of data at a continental level. While this approach enables a broad comparative analysis across major world regions, it inevitably masks substantial intra-regional heterogeneity. Differences in agricultural production systems, farm sizes, climatic conditions, and dominant crop or livestock types within each region may lead to varied sustainability outcomes from digital technology adoption. For instance, digital tools may yield significantly different impacts in intensive commercial farming systems compared to smallholder or subsistence-based agriculture. Consequently, the reported regional trends should be interpreted as indicative rather than representative of all national or sub-regional contexts. Future research would benefit from country-level or production-system-specific analyses to capture these variations more precisely.

Although Europe appears to perform strongly in this study's framework, this position should be interpreted with caution. Broader evidence indicates that Europe faces persistent barriers to digital transformation, particularly in rural infrastructure, interoperability, and investment capacity. The observed advantage therefore reflects targeted sustainability-oriented initiatives, such as precision farming and environmental monitoring, rather than overall digital maturity. These findings highlight a gap between sustainability-driven digital policies and the broader digitalization of the agricultural sector. While the CAP provides a comprehensive European framework linking digital innovation and sustainability, comparable policy instruments exist globally, such as national smart agriculture programs and rural innovation strategies. The comparison of these policy environments underscores that the success of digital sustainability transitions depends not only on technology availability but also on coherent policy integration and local implementation capacity. the analysis reveals differentiated regional pathways toward digital sustainability. Europe's progress is policy-driven but constrained by structural digitalization barriers, whereas other regions, despite lower policy coordination, exhibit rapid grassroots adoption and innovation dynamics.

Future research should build on this study by conducting in-depth regional case studies that explore the specific drivers and barriers to digital technology adoption in diverse agricultural systems. Longitudinal analyses would also be valuable to assess the sustained impact of digital interventions over time. Additionally, sector-specific investigations as examining the effects of precision irrigation, AI-based pest control, or blockchain-enabled supply chains could provide more granular insights. These directions would validate and refine the findings presented here, and offer actionable guidance for policymakers and stakeholders seeking to scale digital solutions effectively across different agricultural contexts.

4 Conclusions

This study looked at how the use of digital tools in agriculture relates to improvements in sustainability across a selection of countries in Europe, the Americas, Asia, and Africa. The results suggest that higher use of digital technologies may be linked to better outcomes in areas like productivity, environmental care, and efficient use of resources. However, since the data shows correlations rather than clear cause-and-effect, these findings should be interpreted with care.

Countries in Europe and parts of North America showed higher levels of digital adoption within the group of respondents included in this research. Still, this does not mean that digitalisation is fully developed across these regions. Other studies show that many farmers in Europe still face challenges, including limited access to infrastructure and funding. It is more accurate to say that, in our sample, some European countries reported more progress in digital adoption compared to others, rather than making broader claims about the whole continent.

We also found that strong support from public policies plays an important role. In places where governments have put in place clear agricultural frameworks, farmers seem better equipped to take advantage of digital tools. For example, both the European Union's Common Agricultural Policy and the United States' Farm Bill provide funding and guidance that help farmers invest in technology. Comparing these policy approaches gives useful insights and helps avoid focusing too much on just one region.

At the same time, this study has its limits. The number of participants from each country was not large enough to represent full national trends. Many of the results are based on averages and self-reported data, and some tools used in the analysis rely on assumptions that could affect the final outcomes. Future work could build on this by using more detailed data, following changes over time, and focusing more on local policy environments. Digital technologies show real potential to support more sustainable farming. But their success depends heavily on the local context. To make real progress, decision-makers should listen to farmers' needs, remove barriers to access, and invest in training and infrastructure that make digital tools useful and effective in everyday practice.

Data availability statement

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

Author contributions

KS-A: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AI: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1655881/full#supplementary-material

References

Abiri, R., Rizan, N., Balasundram, S. K., Shahbazi, A. B., and Abdul-Hamid, H. (2023). Application of digital technologies for ensuring agricultural productivity. *Heliyon* 9:e22601. doi: 10.1016/j.heliyon.2023.e22601

Ahmadi-Gh, Z., and Bello-Pintado, A. (2022). Why is manufacturing not more sustainable? The effects of different sustainability practices on sustainability outcomes and competitive advantage. *J. Clean. Prod.* 337:130392. doi: 10.1016/j.jclepro.2022.130392

Ahmetoglu, S., Che Cob, Z., and Ali, N. (2022). A systematic review of internet of things adoption in organizations: taxonomy, benefits, challenges and critical factors. *Appl. Sci.* 12:4117. doi: 10.3390/app12094117

Akimov, O., and Akimova, L. (2023). *Artificial Intelligence as a Tool of Public Management of Socio-Economic Development: Economic Systems, Smart Infrastructure, Digital Systems of Business Analytics and Transfers*. Cham: Springer Nature.

Alojail, M., and Khan, S. B. (2023). Impact of digital transformation toward sustainable development. *Sustainability* 15:14697. doi: 10.3390/su152014697

AMECO Database (2023). *Annual Macro-Economic Database*. Brussels: European Commission. Available online at: https://economy-finance.ec.europa.eu (Accessed September 6, 2023).

Asian Agri (n.d.). *Sustainability Reports*. Available online at: https://www.asianagri.com/en/sustainability/sustainability-reports/ (Accessed August 7, 2024).

Balasundram, S. K., Shamshiri, R. R., Sridhara, S., and Rizan, N. (2023). The role of digital agriculture in mitigating climate change and ensuring food security: an overview. *Sustainability* 15:5325. doi: 10.3390/su15065325

Barañano, L., Garbisu, N., Alkorta, I., Araujo, A., and Garbisu, C. (2021). Contextualization of the bioeconomy concept through its links with related concepts and the challenges facing humanity. *Sustainability* 13:7746. doi: 10.3390/su13147746

Befort (2020). Going beyond definitions to understand tensions within the bioeconomy: the contribution of sociotechnical regimes to contested fields. *Technol. Forecast. Soc. Change* 153:119923. doi: 10.1016/j.techfore.2020.119923

Bell, J., Paula, L., Dodd, T., Németh, S., Nanou, C., Mega, V., et al. (2018). EU ambition to build the world's leading bioeconomy—Uncertain times demand innovative and sustainable solutions. *New Biotechnol.* 40, 25–30. doi: 10.1016/j.nbt.2017.06.010

Bhagat, P., Naz, F., and Magda, R. (2022). Artificial intelligence solutions enabling sustainable agriculture: A bibliometric analysis. *PLoS ONE* 17:e0268989. doi: 10.1371/journal.pone.0268989

Birner, R., Daum, T., and Pray, C. (2021). Who drives the digital revolution in agriculture? A review of supply-side trends, players and challenges. *Appl. Econ. Perspect. Policy* 43. doi: 10.1002/aepp.13145

Bugge, M. M., Hansen, T., and Klitkou, A. (2016). What is the bioeconomy? A review of the literature. *Sustainability* 8:691. doi: 10.3390/su8070691

CABI (2023). *CABI Environmental Science Database*. Wallingford: CAB International. Available online at: https://www.cabi.org (Accessed June 9, 2023).

Cary, J., Webb, T., and Barr, N. (2001). *The Adoption of Sustainable Practices: Some New Insights. An Analysis of Drivers and Constraints for the Adoption of Sustainable Practices Derived From Research*. Barton: Bureau of Rural Sciences.

Chkarat, H., Abid, T., and Sauvée, L. (2023). Conditions for a Convergence between Digital Platforms and Sustainability in Agriculture. *Sustainability* 15:14195. doi: 10.3390/su151914195

Choubey, A., Wadhwa, S., and Ayam, J. (2024). *IoT-Based Soil Monitoring System & Crop Management*. Available online at: https://www.researchgate.net/publication/380027943_IoT-Based_Soil_Monitoring_System_Crop_Management (Accessed August 1, 2023).

Circular Economy Coalition (n.d.). *Reports on Tools for Promoting the Circular Economy in Agriculture*. Available online at: www.cec.org (Accessed October 17, 2024).

Circularity Gap Report (n.d.). Available online at: https://assets.website-files.com/5e185aa4d27bcf348400ed82/63c6986f0a57abe2fb9180d7_CGR%202023%20-%20Report%20(1).pdf (Accessed August 15, 2024).

Climate FieldView (n.d.). *Insights Into the Application of Precision Agricultural Tools in Sustainability Practices*. Available online at: www.climate.com (Accessed October 17, 2024).

Creswell, J. W. (2002). *Educational Research: Planning, Conducting, and Evaluating Quantitative*. Upper Saddle River, NJ: Prentice Hall.

Crop X (n.d.). *AI-driven Sensors and Data Analytics for Land Use and Water Management in Agriculture*. CropX Smart Agriculture. Available online at: www.cropx.com (Accessed October 17, 2024).

Diakosavvas, D., and Frezal, C. (2019). *Bio-Economy and the Sustainability of the Agriculture and Food System: Opportunities and Policy Challenges*. OECD Food, Agriculture and Fisheries Papers, No. 136. Paris: OECD Publishing.

Díaz-Arancibia, J., Hochstetter-Diez, J., Bustamante-Mora, A., Sepúlveda-Cuevas, S., Albayay, I., and Arango-López, J. (2024). Navigating digital transformation and technology adoption: a literature review from small and medium-sized enterprises in developing countries. *Sustainability* 16:5946. doi: 10.3390/su16145946

Dönmez, D., and Isak, M. A., Izgü, T., and Simşek, Ö. (2024). Green horizons: navigating the future of agriculture through sustainable practices. *Sustainability* 16:3505. doi: 10.3390/su16083505

Du, X., Zhang, H., and Han, Y. (2022). How does new infrastructure investment affect economic growth quality? *Empirical Evidence from China. Sustainability* 14:3511. doi: 10.3390/su14063511

EBSCO Information Services (2023). *EBSCOhost Research Databases*. Ipswich, MA: EBSCO Information Services. Available online at: https://www.ebsco.com (Accessed February 27, 2023).

Egea, F. J., López-Rodríguez, M. D., Oña-Burgos, P., Castro, A. J., and Richard Glass, C. (2021). Bioeconomy as a transforming driver of intensive greenhouse horticulture in SE Spain. *New Biotechnol.* 61:50–56. doi: 10.1016/j.nbt.2020.11.010

Environmental Impact Statement Database (2023). *Environmental Impact Statements Database*. United States Environmental Protection Agency. Available online at: https://www.epa.gov (Accessed August 11, 2023).

European Commision (n.d.). *Reports*. Available online at: https://agriculture.ec.europa.eu/news/commission-launches-new-online-tool-sustainability-agriculture-2024-05-17_en?wt-search=yes (Accessed August 8, 2024).

European Commission (2022). *EU Bioeconomy Strategy Progress Report. European Bioeconomy Policy: Stocktaking and Future Developments*. Available online at: https://knowledge4policy.ec.europa.eu/publication/report-com2022283-eu-bioeconomy-strategy-progress-report-european-bioeconomy-policy_e

European Environment Agency (2018). *The circular economy and the bioeconomy - Partners in Sustainability*. Luxembourg: European Environment Agency.

EUROSTAT (n.d.). Available online at: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240619-3 (Accessed August 9, 2024).

Fabiani, S., Vanino, S., Napoli, R., Zajíček, A., Duffková, R., Evangelou, E., et al. (2020). Assessment of the economic and environmental sustainability of Variable Rate Technology (VRT) application in different wheat intensive European agricultural areas. A Water energy food nexus approach. Environ. Sci. *Policy* 114, 366–376. doi: 10.1016/j.envsci.2020.08.019

FiBL (n.d.). Available online at: https://www.fibl.org/en/info-centre/news/2022-more-than-10-percent-eu-farmland-organic (Accessed August 14, 2024).

FIBL (n.d.). Available online at: https://orgprints.org/id/eprint/51607/1/willer-etal-2023-statisticalyearbook-africa.pdf (Accessed August 9, 2024).

Fielke, S., Taylor, B., and Jakku, E. (2020). Digitalisation of agricultural knowledge and advice networks: a state-of-the-art review. *Agric. Syst.* 180:102763. doi: 10.1016/j.agsy.2019.102763

Fiscal Governance Database (2023). *Fiscal Governance Database*. International Monetary Fund. Available online at: https://www.imf.org (Accessed October 2, 2023).

Food and Agriculture Organization (n.d.). Available online at: https://www.fao.org/home/en (Accessed August 2, 2024).

Food and Agriculture Organization of the United Nations (2023). *FAOSTAT Statistical Database*. Rome: FAO. Available online at: https://www.fao.org/faostat (Accessed May 18, 2023).

Frisvold, G. B., Moss, S. M., Hodgson, A., and Maxon, M. E. (2021). Understanding the U.S. bioeconomy: a new definition and landscape. *Sustainability* 13:1627. doi: 10.3390/su13041627

Gawel, E., Pannicke, N., and Hagemann, N. (2019). A Path Transition Towards a Bioeconomy—The Crucial Role of Sustainability. *Sustainability* 11:3005. doi: 10.3390/su11113005

Gebresenbet, G., Bosona, T., Patterson, D., Persson, H., Fischer, B., Mandaluniz, N., et al. (2023). A concept for application of integrated digital technologies to enhance future smart agricultural systems. *Smart Agric. Technol.* 5:100255. doi: 10.1016/j.atech.2023.100255

Giuliani, A., and Baron, H. (2023). The CAP (Common Agricultural Policy): a short history of crises and major transformations of European Agriculture. *Forum Soc. Econ.* 54:1–27. doi: 10.1080/07360932.2023.2259618

Global Environmental Database (2023). *Global Environmental Data Repository*. United Nations Environment Programme. Available online at: https://www.unep.org (Accessed July 3, 2023).

Golden Agri-Resources Ltd (n.d.). *Sustainability Reports*. Available online at: https://www.goldenagri.com.sg/sustainability/sustainability-report/ (Accessed August 9, 2024).

Golembiewski, B., Sick, N., and Bröring, S. (2015). Patterns of Convergence Within the Emerging Bioeconomy — The Case of the Agricultural and Energy Sector. *Int. J. Innov. Technol. Manag.* 12:1550012. doi: 10.1142/S0219877015500121

Goller, M., Caruso, C., and Harteis, C. (2021). Digitalisation in agriculture: knowledge and learning requirements of German dairy farmers. *Int. J. Res. Vocat. Educ. Train.* 8, 208–223. doi: 10.13152/IJRVET.8.2.4

Hariram, N. P., Mekha, K. B., Suganthan, V., and Sudhakar, K. (2023). Sustainalism: an integrated socio-economic-environmental model to address sustainable development and sustainability. *Sustainability* 15:10682. doi: 10.3390/su151310682

Hauser, J., and Katz, G. (1998). Metrics: you are what you measure! *Eur. Manag. J.* 16, 517–528. doi: 10.1016/S0263-2373(98)00029-2

Hong, Y., Tu, J., and Zhou, G. (2006). Asymmetries in stock returns: statistical tests and economic evaluation. *J. Empir. Finan.* 13, 537–555. doi: 10.1016/j.jempfin.2006.01.002

International Energy Agency (2023). *IEA Data and Statistics*. Paris: International Energy Agency. Available online at: https://www.iea.org (Accessed April 5, 2023).

Islam, M. R., Oliullah, K., Kabir, M. M., Alom, M., and Mridha, M. F. (2023). Machine learning enabled IoT system for soil nutrients monitoring and crop recommendation. *J. Agric. Food Res.* 14:100880. doi: 10.1016/j.jafr.2023.100880

Kaboré, S. S., Ngangue, P., Soubeiga, D., Barro, A., Pilabré, A. H., Bationo, N., et al. (2022). Barriers and facilitators for the sustainability of digital health interventions in low and middle-income countries: A systematic review. *Front. Digit. Health* 4:1014375. doi: 10.3389/fdgth.2022.1014375

Kalluri, R. C. (2023). An impact of digital technology in sustainable business development. *J. Law Sustain. Dev.* 11:e2696. doi: 10.55908/sdgs.v11i12.2696

Kamakaula, Y. (2024). Sustainable agriculture practices: economic, ecological, and social approaches to enhance farmer welfare and environmental sustainability. *West Sci. Nat. Technol.* 2, 47–54. doi: 10.58812/wsnt.v2i02.964

Karuna, G., Kumar, R., Sanjeeva, P., Deepthi, P., Saeed, H., V, A., et al. (2024). Crop recommendation system and crop monitoring using IoT. *E3S Web Conf.* 507:01063. doi: 10.1051/e3sconf/202450701063

Karunathilake, E. M. B. M., Le, A. T., Heo, S., Chung, Y. S., and Mansoor, S. (2023). The Path to Smart Farming: Innovations and Opportunities in Precision Agriculture. *Agriculture* 13:1593. doi: 10.3390/agriculture13081593

Katz, R. L., and Koutroumpis, P. (2013). Measuring digitalization, A growth and welfare multiplier. *Technovation* 33, 314–319. doi: 10.1016/j.technovation.2013.06.004

Kim, K., and Kim, B. (2022). Decision-making model for reinforcing digital transformation strategies based on artificial intelligence technology. *Information* 13:253. doi: 10.3390/info13050253

Knell, M. (2021). The digital revolution and digitalized network society. *Rev. Evol. Polit. Econ.* 2, 9–25. doi: 10.1007/s43253-021-00037-4

Kuhlman, T., and Farrington, J. (2010). What is sustainability? *Sustainability* 2, 3436–3448. doi: 10.3390/su2113436

Kumar, R. (2018). *Research Methodology: A Step-by-Step Guide for Beginners*. New York, NY: Sage.

Liobikiene, G., Miceikiene, A., and Brizga, J. (2021). Decomposition analysis of bioresources: Implementing a competitive and sustainable bioeconomy strategy in the Baltic Sea Region. *Land Use Policy* 108:105565. doi: 10.1016/j.landusepol.2021.105565

MacPherson, J., Voglhuber-Slavinsky, A., Olbrisch, M., Schöbel, P., Dönitz, E., Mouratiadou, I., et al. (2022). Future agricultural systems and the role of digitalization for achieving sustainability goals. A review. *Agron. Sustain. Dev.* 42:70. doi: 10.1007/s13593-022-00792-6

Mana, A. A., Allouhi, A., Hamrani, A., Rehman, S., el Jamaoui, I., and Jayachandran, K. (2024). Sustainable AI-based production agriculture: Exploring AI applications and implications in agricultural practices. *Smart Agric. Technol.* 7:100416. doi: 10.1016/j.atech.2024.100416

Manheim, D. (2023). Building less-flawed metrics: Understanding and creating better measurement and incentive systems. *Patterns* 4:100842. doi: 10.1016/j.patter.2023.100842

Mao, X. (2023). Analysis of the influence path of digital infrastructure on economic development. *Adv. Econ. Manag. Political Sci.* 25, 47–55. doi: 10.54254/2754-1169/25/20230474

Marcet Research Intellect (n.d.). Available online at: https://www.marketresearchintellect.com/product/global-precision-farming-agriculture-market-size-and-forecast/ (Accessed August 12, 2024).

Martínez-Peláez, R., Ochoa-Brust, A., Rivera, S., Félix, V. G., Ostos, R., Brito, H., et al. (2023). Role of digital transformation for achieving sustainability: mediated role of stakeholders, key capabilities, and technology. *Sustainability* 15:11221. doi: 10.3390/su151411221

Mboli, J. S., Dhavalkumar, T., and Mishra, J. L. (2022). An Internet of Things-enabled decision support system for circular economy business model. *Softw. Pract. Exp.* 52, 772–787. doi: 10.1002/spe.2825

McCampbell, M., Adewopo, J., Klerkx, L., and Leeuwis, C. (2021). Are farmers ready to use phone-based digital tools for agronomic advice? Ex-ante user readiness assessment using the case of Rwandan banana farmers. *J. Agric. Educ. Ext.* doi: 10.1080/1389224X.2021.1984955

McCampbell, M., Adewopo, J., Klerkx, L., and Leeuwis, C. (2023). Are farmers ready to use phone-based digital tools for agronomic advice? Ex-ante user readiness assessment using the case of Rwandan Banana Farmers. *J. Agric. Educ. Ext.* 29, 29–51.

Mccormick, K., and Kautto, N. (2013). The Bioeconomy in Europe: An Overview. *Sustainability* 5, 2589–2608. doi: 10.3390/su5062589

Muhie, S. H. (2022). Novel approaches and practices to sustainable agriculture. *J. Agric. Food Res.* 10:100446. doi: 10.1016/j.jafr.2022.100446

Nambisan, S., Wright, M., and Feldman, M. (2019). The digital transformation of innovation and entrepreneurship: progress, challenges and key themes. *Res. Policy* 48, 1–9. doi: 10.1016/j.respol.2019.03.018

Neves, C., Oliveira, T., and Santini, F. (2022). Sustainable technologies adoption research: A weight and meta-analysis. *Renew. Sustain. Energy Rev.* 165:112627. doi: 10.1016/j.rser.2022.112627

Obaisi, A., Adegbeye, M., Elghandour, M. M. M. Y., Barbabosa-Pliego, A., and Salem, A. (2022). "Natural resource management and sustainable agriculture," in *Handbook of Climate Change Mitigation and Adaptation* (Springer), 2577–2613.

Organisation for Economic Co-operation and Development (2023). *OECD Data*. Paris: OECD Publishing. Available online at: https://data.oecd.org (Accessed November 20, 2023).

Papadopoulos, G., Arduini, S., Uyar, H., Psiroukis, V., Kasimati, A., and Fountas, S. (2024). Economic and environmental benefits of digital agricultural technologies in crop production: a review. *Smart Agric. Technol.* 8:100441. doi: 10.1016/j.atech.2024.100441

Pe'er, G., Bonn, A., Bruelheide, H., Dieker, P., Eisenhauer, N., Feindt, P. H., et al. (2020). Action needed for the EU common agricultural policy to address sustainability challenges. *People Nat.* 2, 305–316. doi: 10.1002/pan3.10080

Peng, Y., Fayaz Ahmad, S., Irshad, M., Al-Razgan, M., Ali, Y., and Awwad, E. (2023). Impact of digitalization on process optimization and decision-making towards sustainability: the moderating role of environmental regulation. *Sustainability* 15:15156. doi: 10.3390/su152015156

Pereira, C. S., Durão, N., Moreira, F., and Veloso, B. (2022). The importance of digital transformation in international business. *Sustainability* 14:834. doi: 10.3390/su14020834

Piacentini, R. D., and Della Ceca, L. S. (2017). The use of environmental sustainability criteria in industrial processes. *Dry. Technol.* 35, 1–3. doi: 10.1080/07373937.2016.1243446

Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A. M., Kinengyere, A., et al. (2020). A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. *Nat. Sustain.* 3, 809–820. doi: 10.1038/s41893-020-00617-y

Plekhanov, D., Franke, H., and Netland, T. H. (2023). Digital transformation: a review and research agenda. *Eur. Manag. J.* 41, 821–844. doi: 10.1016/j.emj.2022.09.007

Prakasa Rao, B. L. S. (2021). Nonparametric estimation for stochastic differential equations driven by mixed fractional brownian motion with random effects. *Sankhya A Indian J. Stat.* 83, 554–568. doi: 10.1007/s13171-020-00230-3

ProQuest Natural Sciences Database (2023). *ProQuest Natural Sciences Collection*. Ann Arbor, MI: ProQuest LLC. Available online at: https://www.proquest.com (Accessed January 15, 2025).

Qi, Z., and You, Y. (2024). The impact of the rural digital economy on agricultural green development and its mechanism: empirical evidence from China. *Sustainability* 16:3594. doi: 10.3390/su16093594

Qiu, Z., Wang, S., Hou, Y., and Xu, S. (2023). What Drives Infrastructure Participants to Adopt Digital Technology: A Nexus of Internal and External Factors. *Sustainability* 15, 16229. doi: 10.3390/su152316229

Rajak, P., Ganguly, A., Adhikary, S., and Bhattacharya, S. (2023). Internet of Things and smart sensors in agriculture: Scopes and challenges. *J. Agric. Food Res.* 14:100776. doi: 10.1016/j.jafr.2023.100776

Rennings, M., Burgsmüller, A. P. F., and Bröring, S. (2023). Convergence towards a digitalized bioeconomy—Exploring cross-industry merger and acquisition activities between the bioeconomy and the digital economy. *Bus. Strategy Dev.* 6, 53–74. doi: 10.1002/bsd2.223

Rojas-Serrano, F., Garcia-Garcia, G., Parra-López, C., and Sayadi, S. (2024). Sustainability, circular economy and bioeconomy: A conceptual review and integration into the notion of sustainable circular bioeconomy. *New Medit.* 23, 3–22. doi: 10.30682/nm2402a

Rolandi, S., Brunori, G., Bacco, M., and Scotti, I. (2021). The digitalization of agriculture and rural areas: towards a taxonomy of the impacts. *Sustainability* 13:5172. doi: 10.3390/su13095172

Rosati, P., Lynn, T., Kreps, D., and Conboy, K. (2024). "Digital Sustainability: Key Definitions and Concepts," in *Digital Sustainability*, eds. T. Lynn, P. Rosati, D. Kreps, and K. Conboy (Cham: Palgrave Macmillan).

Sharma, V., Kumar Tripathi, A., and Mittal, H. (2022). Technological revolutions in smart farming: Current trends, challenges & future directions. *Comput. Electron. Agric.* 201:107217. doi: 10.1016/j.compag.2022.107217

Slavova, P., and Barrett, C. B. (2011). "Frictions in agricultural value chains," in *Food Policy and Price Volatility*, eds. J. von Braun and R. Vargas Hill (Abingdon: Routledge), 105–132.

Soori, P. K., Arezoo, B., and Dastres, R. (2024). Artificial intelligence, blockchain, and IoT for sustainable agriculture: a review. *Sustain. Futures* 6:100154. doi: 10.1016/j.sftr.2024.100154

STATISTA (n.d.a). Available online at: https://www.statista.com/statistics/677969/organic-agricultural-land-worldwide-leading-countries/ (Accessed August 12, 2024).

STATISTA (n.d.b). *Comprehensive Market Trends and Statistical Data on Agricultural Technology*. Statista Digital Agriculture Reports. Available online at: www.statista.com (Accessed October 17, 2024).

Tan, E. C. D., and Lamers, P. (2021). Circular bioeconomy concepts—a perspective. *Front. Sustain.* 2:701509. doi: 10.3389/frsus.2021.701509

Teagasc (n.d.). *Sustainability Reports*. Available online at: https://www.teagasc.ie/rural-economy/rural-economy/national-farm-survey/sustainability-reports/ (Accessed August 7, 2024).

Trendov, M. N., Samuel, V., and Meng, Z. (2019). *Digital Technologies in Agriculture and Rural Areas Briefing Paper*. Rome: Food and Agriculture Organization of the United Nations.

Trigo, E., Chavarria, H., Pray, C., Smyth, S. J., Torroba, A., Wesseler, J., et al. (2023). The bioeconomy and food systems transformation. *Sustainability* 15:6101. doi: 10.1007/978-3-031-15703-5_45

Trimble Agriculture Solutions (n.d.). *Reports on Advanced Digital Tools for Resource Management and Precision Farming*. Available online at: www.trimble.com (Accessed October 17, 2024).

Tsegaye, B., Jaiswal, S., and Jaiswal, A. K. (2021). Food waste biorefinery: Pathway towards circular bioeconomy. *Foods* 10:1174. doi: 10.3390/foods10061174

TWI2050 (2019). *The Digital Revolution and Sustainable Development: Opportunities and Challenges*. Laxenburg: International Institute for Applied Systems Analysis (IIASA). Available online at: www.twi2050.org (Accessed August 3, 2024).

TWI2050 (2020). *Innovations for Sustainability. Pathways to an Efficient and Post-pandemic Future.* Laxenburg: International Institute for Applied Systems Analysis (IIASA). Available online at: https://pure.iiasa.ac.at/id/eprint/16533/ (Accessed October 25, 2024).

United Nations (1987). *Report of the World Commission on Environment and Development: Our Common Future*. Available online at: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf (Accessed August 5, 2024).

Varga, P., Kún, G., and Moldován, I. (2006). "Correlation of bottleneck metrics and quality of experience," in *Proceedings of the International Conference on Software in Telecommunications and Computer Networks (SoftCOM)* (New York, NY: IEEE).

von Braun, J., Zamagni, S., and Sorondo, M. S. (2020). The moment to see the poor. *Science* 368:214. doi: 10.1126/science.abc2255

Wang, W., and Mei, T. (2024). Research on the effect of digital economy development on the carbon emission intensity of agriculture. *Sustainability* 16:1457. doi: 10.3390/su16041457

Wang, Z., Zhang, J., He, Y., and Liu, H. (2024). A study on the potential of digital economy in reducing agricultural carbon emissions. *Heliyon* 10:e31941. doi: 10.1016/j.heliyon.2024.e31941

Watanabe, C., Naveed, N., and Neittaanmäki, P. (2018). Digital solutions transform the forest-based bioeconomy into a digital platform industry - A suggestion for a disruptive business model in the digital economy. *Technol. Soc.* 54, 168–188. doi: 10.1016/j.techsoc.2018.05.002

Wei, X., Luo, J., Pu, A., Liu, Q., Zhang, L., Wu, S., et al. (2022). From Biotechnology to Bioeconomy: A Review of Development Dynamics and Pathways. *Sustainability* 14:10413. doi: 10.3390/su141610413

Wijerathna-Yapa, A., and Pathirana, R. (2022). Sustainable agro-food systems for addressing climate change and food security. *Agriculture* 12:1554. doi: 10.3390/agriculture12101554

World Bank Group (2023). *World Bank Open Data*. Washington, DC: World Bank Group. Available online at: https://www.worldbank.org (Accessed March 12, 2023).

World Economic Outlook Database (2023). *World Economic Outlook Database*. Washington, DC: International Monetary Fund. Available online at: https://www.imf.org (Accessed October 15, 2023).

Zabaniotou, A. (2018). Redesigning a bioenergy sector in EU in the transition to circular waste-based bioeconomy-a multidisciplinary review. *J. Clean. Prod.* 177, 197–206. doi: 10.1016/j.jclepro.2017.12.172

Zeverte-Rivza, S., Girdziute, L., Parlińska, A., Rivza, P., Novikova, A., and Gudele, I. (2023). Digitalisation in Bioeconomy in the Baltic States and Poland. *Sustainability* 15:13237. doi: 10.3390/su151713237