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Integrating digital technologies in agriculture for climate change adaptation and mitigation: State of the art and future perspectives

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HIGHLIGHTS

- Agriculture must evolve to adapt to and mitigate climate change (CC).
- Digital technologies (DT) can support agriculture in CC adaptation and mitigation.
- Key DT applications for CC adaptation and mitigation are reviewed.
- Opportunities and barriers for DT adoption are discussed.
- Future actions to support the integration of DT in agriculture are proposed.

ABSTRACT

Agriculture faces a major challenge in meeting the world's growing demand for food in a sustainable manner in the face of increasing environmental pressures, in particular the growing impact of climate change. Agriculture is also a major contributor to climate change. Digital technologies in agriculture can contribute to climate change adaptation and mitigation. This paper examines the interactions between climate change and agriculture, reviews adaptation and mitigation strategies, explores the application of digital technologies in this context, and discusses future challenges and opportunities for sustainable and resilient agriculture. The final aim is to provide a comprehensive overview of the current state and future prospects of digital agriculture in the context of climate change. A comprehensive literature review was conducted on adaptation and mitigation strategies in agriculture, and on the current state and future prospects of digital agriculture in the context of climate change adaptation and mitigation. The identified applications of digital technologies in agriculture include Remote Sensing for crop monitoring, Big Data for predictive modelling of water shortages and pest outbreaks, Artificial Intelligence for pest identification and tracking, the Internet of Things for precision fertiliser management, nanotechnology for soil improvement, robots for targeted spraying, and blockchain for improved soil management and supply chain transparency, among others. These technologies facilitate the precise management of resources, improve decision-making processes and enable more efficient agricultural practices. Digital technologies also help mitigate climate change by optimising inputs such as water and fertiliser, thereby reducing greenhouse gas emissions and promoting carbon sequestration. However, there are significant barriers to the adoption of these technologies, including the digital divide, high up-front costs and complexity, as well as privacy and security concerns and the environmental impact of technology use. Future action must address these barriers by investing in infrastructure and training, ensuring financial incentives, developing scalable digital solutions tailored to local agricultural conditions, increasing digital literacy among farmers, developing comprehensive governance frameworks, and exploring the integration of multiple digital technologies. The paper contributes to advancing scientific understanding and guiding practice and policy towards sustainable agriculture in the face of climate change. It provides a call to action for a more sustainable future in the context of climate change and highlights the urgency of multi-stakeholder collaboration to create an enabling environment for the widespread adoption of these innovations, ensuring that they are accessible, cost-effective and suitable for different farming environments.

Keywords: Agriculture 4.0; climate change; digital transformation; digitalisation; sustainability.

Integrating digital technologies in agriculture for climate change adaptation and mitigation: State of the art and future perspectives

1 Introduction

Agriculture is at a critical juncture globally as it strives to meet the growing demand for food and agricultural commodities in a sustainable manner (Jararweh et al., 2023; Wakweya, 2023). With the world's population projected to reach nearly 10 billion by 2050, up from 8 billion in 2022 (United Nations, 2022), it is imperative to adopt sustainable agricultural practices that ensure food security while minimising environmental impacts. Soil erosion, resource depletion, water scarcity and biodiversity loss are major threats to the foundations of agricultural systems (Aguilera et al., 2020; Wang, 2022). The Food and Agriculture Organization of the United Nations (FAO) reports that about 33% of the world's soils are moderately to severely degraded (FAO, 2021). Overuse of fertilisers and pesticides exacerbates ecosystem degradation, leading to water pollution and the loss of beneficial ecosystems such as pollinators and natural pest controls (Tripathi et al., 2020; Tudi et al., 2021). In addition, resource scarcity, particularly water, is becoming a critical constraint on agriculture. According to FAO (2021), agriculture accounts for about 70% of all surface and groundwater withdrawals, mainly for irrigation. The availability of water for agriculture is becoming increasingly uncertain due to increased competition for water from other sectors.

Climate change is exacerbating the challenges facing agriculture worldwide (Hassoun et al., 2022). It poses significant threats to agriculture, including rising temperatures, changes in weather patterns, more frequent extreme events, and changes in pest dynamics that threaten food security and the livelihoods of farming communities worldwide (Balasundram et al., 2023; IPCC, 2019). The ever-changing climate poses a significant challenge to food production, directly affecting crop yields (Muluneh, 2021). The impact of climate change on agriculture is particularly acute in developing countries based on subsistence agriculture, where farmers are highly dependent on weather conditions (Jatav, 2024; Watson, 2014). Indeed, water scarcity is expected to worsen in arid and semi-arid regions, where some of the most food insecure populations live (FAO, 2021). Conversely, agriculture contributes to climate change mainly through various practices that emit greenhouse gases (GHG) (Lynch et al., 2021). In fact, agriculture is responsible for about 30% of global anthropogenic emissions when direct and indirect emissions are taken into account (Lal, 2021). The result is a vicious cycle in which agriculture affects climate change and climate change affects agriculture. This interdependence creates a complex scenario in which the agricultural sector must evolve to combat and adapt to climate change

(Yohannes, 2016). Breaking this cycle is challenging as it requires cross-sectoral efforts at regional and global levels, as well as the development and implementation of innovative and sustainable practices that reduce GHG emissions and build resilience to the impacts of a changing climate.

Digital agriculture is the application of digital technologies in the agricultural sector, forming a paradigm commonly referred to as Agriculture 4.0. These digital technologies mostly include Artificial Intelligence (AI), Big Data (BD), Internet of Things (IoT), Remote Sensing (RS) and other advanced technologies that are transforming the production, marketing and consumption of food. These technologies represent new technological solutions in agriculture, such as smart irrigation, crop and pest forecasting, robotic pest control, smart harvesting and improved traceability from farm to fork, among others (Hassoun et al., 2023b; Parra-López et al., 2021). The use of such technologies in agriculture has recently led to the emergence of innovative concepts such as precision agriculture and smart farming.

Digital technologies are increasingly being used to address the many challenges facing the food sector, in particular climate change and related issues such as biodiversity loss, soil erosion, global warming, storms and droughts, among others (Inoue, 2020; Jung et al., 2021; Pandey and Pandey, 2023; Radoglou-Grammatikis et al., 2020). Indeed, digital technologies can facilitate adaptation strategies, which are crucial for managing vulnerabilities and increasing the resilience of agricultural systems to climate change (Basso and Antle, 2020). In addition, these technologies can contribute to mitigation by reducing GHG emissions and promoting carbon sequestration in agricultural landscapes (Balasundram et al., 2023; Thamarai et al., 2024).

Although there is a considerable body of literature on the use of digital technologies in agriculture to address climate change, many studies on this topic are often partial in that they focus exclusively on one or a few specific individual technologies and consider only limited or indirect aspects of either climate change adaptation or mitigation (Elbasi et al., 2023; Iwasaki et al., 2024; Omia et al., 2023; Patel et al., 2023). This highlights the need for more integrative and holistic research covering a wide range of digital technologies and their impacts on both climate change adaptation and mitigation in the agricultural sector. First, there is a need for a review that clarifies the mechanisms through which digital agriculture can impact on climate change. This involves synthesising existing research to provide a holistic understanding of how different digital technologies contribute to adaptation and mitigation strategies. Secondly, a comprehensive review is needed to identify both the opportunities and challenges associated with the use of digital agricultural technologies to address climate change. Finally, a review is needed to identify gaps in current research, which can help to outline future research directions. This study aims to contribute to filling these research gaps by providing a comprehensive, integrative and global

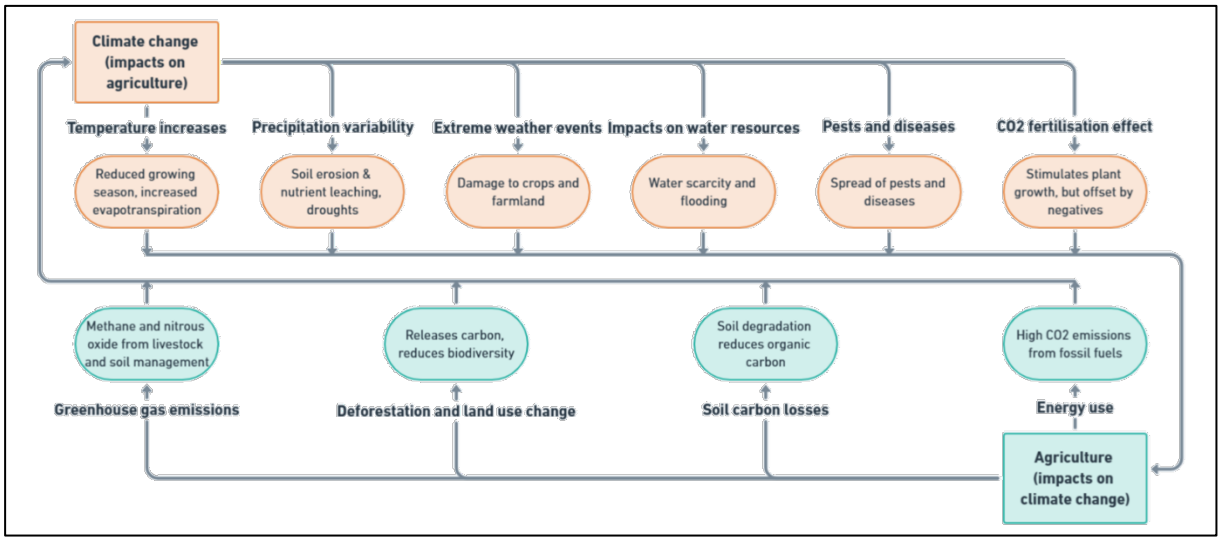
perspective on the role of digital technologies in agricultural climate change adaptation and mitigation.

In this context, this paper has four main objectives: 1) to analyse the dynamic interactions between climate change and agriculture, with a focus on detailing how climate change affects agriculture and vice versa; 2) to describe climate change adaptation and mitigation strategies in agriculture, including an in-depth and updated review of current and emerging strategies; 3) to explore specific applications of digital technologies for climate change adaptation and mitigation in agriculture, describing specific cases; and 4) to discuss future challenges and opportunities for integrating digital innovations in agriculture, with the aim of identifying emerging trends that could transform agriculture in terms of sustainability and resilience to climate change and contribution to its mitigation. The final aim is to elucidate the broader, systemic impacts of digital agricultural technologies on climate change adaptation and mitigation by identifying key processes and interactions that may be overlooked in individual studies. It aims to provide a balanced view by highlighting the potential benefits and opportunities as well as the challenges of implementing these technologies. It also aims to identify under-explored areas and potential synergies in existing research, thereby setting an agenda for future studies. This comprehensive approach aims to inform stakeholders and policy makers about both the promise and limitations of digital agriculture in addressing climate change, and ultimately to guide future research efforts to fully realise the potential of these technologies.

2 Relationship between climate change and agriculture

Climate change can be defined as a significant and persistent change in the Earth's climate and weather patterns. It encompasses a wide range of changes, including global warming, extreme weather events such as floods, droughts and heat waves, changes in precipitation patterns and shifts in other climatic phenomena over time (Rummukainen, 2012; Stott, 2016; Weber, 2010). Climate change is driven by a combination of natural processes and human activities, in particular the emission of GHG, mainly carbon dioxide (CO_2) but also others such as methane (CH_4) and nitrous oxide (N_2O), which have increased since the industrial revolution (Shakoor et al., 2020). They affect many aspects of the natural world and human life, including ecosystem functioning, biodiversity, human health and economic activities (Barbieri et al., 2024; Kone et al., 2024; Malhi et al., 2021; Meyer, 1995; Tol, 2018; Wu et al., 2016). Climate change and agriculture are closely linked, with each having a significant impact on the other, as summarised in Figure 1 and described in the following sections.

Figure 1. Main interactions between climate change and agriculture



Source: Own elaboration.

2.1 Impact of climate change on agriculture

Climate change has significant implications for agriculture, which is highly dependent on climatic conditions. First, rising temperatures can reduce the length of the growing season, leading to premature maturation and lower yields (Lobell et al., 2011; Saadi et al., 2015). Crops such as wheat and maize are particularly sensitive to rising temperatures, with yields declining in some regions (Asseng et al., 2015; Bassu et al., 2014). Higher temperatures also increase evapotranspiration rates, exacerbating water scarcity and increasing crop water demand, putting additional pressure on water resources (Lobell et al., 2011).

Moreover, changes in precipitation patterns pose a dual challenge: increased rainfall aggressiveness in some regions leads to waterlogging, soil erosion and nutrient leaching (Diodato et al., 2011; Riquetti et al., 2020), while decreased rainfall leads to droughts, particularly in subtropical regions (Trenberth, 2011). This unpredictability complicates agricultural management and planning, with significant implications for food security and farmers' livelihoods (Affoh et al., 2022; Brown and Funk, 2008).

In addition, the frequency and intensity of extreme weather events such as storms, floods and droughts have increased and are likely to continue to increase (Furtak and Wolińska, 2023; Goodess, 2013; Mirzabaev et al., 2023; Stott, 2016). These events cause direct damage to crops and farmland, leading to significant losses in agricultural productivity (De Winne and Peersman, 2021; Sheng and Xu, 2019). Destruction of infrastructure and long-term degradation of land make recovery difficult and affect future production potential (Clarke and Rendell, 2007; Diakakis et al.,

2016; Panteli and Mancarella, 2015). In addition, changes in precipitation patterns and higher temperatures leading to increased evaporation may lead to water scarcity in some areas and flooding in others (Lu et al., 2019). Increased variability in water supply threatens the sustainability of agriculture, especially for farming systems in arid and semi-arid regions (Herrera-Pantoja and Hiscock, 2015; Rezaei et al., 2023).

Warmer and wetter climates are increasing the ability of many pests and diseases to survive and spread (Robinet and Roques, 2010; Skendžić et al., 2021). Changes in pest populations and disease vectors due to climate variability pose additional challenges to crop health and productivity (Garrett et al., 2006; Skendžić et al., 2021). These changes will require new strategies for pest and disease management and will increase reliance on chemical pesticides, which can have negative environmental and human health impacts (Chakraborty and Newton, 2011).

Finally, while increased CO_2 levels due to climate change can stimulate plant growth and potentially increase yields (a phenomenon known as the CO_2 fertilisation effect), the benefits are often offset by the negative effects of higher temperatures and reduced water availability (Lenka and Lal, 2012; Long et al., 2004).

2.2 Impact of agriculture on climate change

Agriculture has a significant impact on climate change through a number of different mechanisms. One of the most important impacts of agriculture on climate change is the emission of GHG, particularly methane and nitrous oxide (Kebreab et al., 2006), mainly from animal husbandry and soil management. Methane is a by-product of the digestive processes (enteric fermentation) of ruminants such as cows and sheep and is a major source of emissions (Saggar et al., 2004). On the other hand, the process of manure management (storage and treatment) produces both methane and nitrous oxide (Monteny et al., 2001). In addition, the application of synthetic fertilisers and the deposition of animal excreta on agricultural soils are important sources of nitrous oxide emissions (De Cara et al., 2005). Otherwise, waterlogged conditions in rice fields create anaerobic environments favourable to methane production (Malyan et al., 2016). Methane and nitrous oxide are of particular concern because of their high global warming potential, which far exceeds that of carbon dioxide (Oshita et al., 2014).

Otherwise, agricultural expansion often requires deforestation, which has two negative effects: it releases significant amounts of carbon stored in forest biomass and soils into the atmosphere, and it reduces biodiversity (Molotoks et al., 2018). Forest loss not only contributes to increased atmospheric CO_2 concentrations, but also reduces the Earth's capacity to absorb

existing CO_2, exacerbating global warming (House et al., 2002). In addition, biodiversity loss reduces the resilience of ecosystems to climate change and reduces their ability to sequester carbon, further contributing to climate change (Tilman et al., 2001). Conversion to agriculture is a major driver of deforestation, particularly in the tropics, where it is fuelled by the demand for more land for cultivation and grazing (Barbier, 2004; Pendrill et al., 2022).

Soil carbon plays a crucial role in regulating atmospheric CO_2 levels, so its loss has a significant impact on carbon cycling and storage. Intensive agricultural practices such as conventional soil management (intensive tillage) and overgrazing, degrade soils and reduce their organic carbon content. Intensive tillage exposes soil organic matter to oxygen, accelerating its decomposition and releasing CO_2 (Nath and Lal, 2017; Willekens et al., 2014; Zhang et al., 2018). This impact is significant globally, as soils are one of the largest reservoirs of organic carbon (Baldock, 2007).

In addition, modern agricultural techniques rely heavily on fossil fuels. From the production of synthetic fertilisers and pesticides and the pumping of water for irrigation, to the operation of farm machinery and the transport of agricultural products, energy use in agriculture is substantial (Peduzzi and Harding Rohr Reis, 2012; Woods et al., 2010). This dependence results in significant CO_2 emissions directly linked to the burning of fossil fuels. Improving energy efficiency in the agricultural sector and increasing the use of renewable energy sources are essential to reduce the depletion of resources, especially those of fossil origin (Chel and Kaushik, 2011).

3 Climate change adaptation and mitigation strategies in agriculture

In response to the challenges facing agriculture under climate change, stakeholders are exploring and evaluating different adaptation and mitigation strategies (Zhang et al., 2020). There is an urgent need for effective ways to promote climate-smart technologies, reduce risks and increase the resilience of agricultural systems to environmental and biotic stresses (Ginigaddara & Kodithuwakku, 2024; Li et al., 2015). However, the challenges and appropriate strategies vary widely across regions, crop types and farming systems, adding complexity to the selection of appropriate approaches.

In this context, a literature review on adaptation and mitigation strategies in agriculture was conducted. The Web of Science and Scopus databases were searched using the following query (search in 'all fields'): (“climate change adaptation” OR “climate change mitigation”) AND (agriculture) AND (strategies). The main themes of this research area were then identified:

adaptation strategies, mitigation techniques and a combination of both. A specific search was then carried out for each topic using the following terms: 1) "climate change adaptation" AND "strategies" AND "agriculture"; 2) "climate change mitigation" AND "strategies" AND "agriculture"; 3) "climate change adaptation and mitigation" AND "strategies" AND "agriculture". Table 1 provides a detailed summary of the results of the review process, which are further explored in the following sections.

Table 1. Climate change adaptation and mitigation strategies in agriculture

Category	Strategy	Techniques and practices	Contribution related to climate change
Adaptation	Crop improvement	Genetic and non-genetic crop improvement, adjustment of cropping calendar, relocation of agricultural production	Increases crop resilience to environmental stresses such as drought, salinity, flooding
	Improved water use and management	Water-saving technologies (drip, sprinkler, micro-irrigation), deficit and precision irrigation, use of non-conventional water resources (treated wastewater, desalinated seawater)	Addresses water scarcity and improves water use efficiency, but raises concerns about energy use and GHG emissions
	Soil health management	No-tillage, minimum tillage, residue retention, windbreaks	Improves soil organic carbon, water use efficiency protection of crops from erosion and crop productivity
	Diversification	Agroforestry, mixed crop-livestock systems, intercropping, crop rotation	Minimises input requirements, stabilises yields and supports biodiversity and ecosystem services
	Other adaptation strategies	Early warning of natural disasters, optimisation of harvests, quality, transparency and traceability	Predicts risks, improves harvests, quality, transparency and traceability
Mitigation	Soil carbon sequestration	No-tillage, crop residue retention, crop rotation, biochar, integrated nutrient management	Reduces GHG emissions by increasing soil organic carbon
	Livestock emissions reduction	Dietary improvements, methane inhibitors, precision animal husbandry and feeding, manure management for biogas production	Reduces methane and other GHG emissions from the livestock sector
	Sustainable use of agricultural inputs	Organic and integrated farming practices, less energy-intensive practices	Reduces environmental impacts of nitrogen fertilisers, fossil fuels and pesticides
	Land use change	Afforestation, reforestation, crop systems change	Increases mitigation potential by changing land use to absorb more CO_2
	Other mitigation strategies	Promotion of environmentally friendly farming systems	Reduces environmental impact and promotes agricultural sustainability
Adaptation and mitigation	Integrated strategies	Integration of effective adaptation and mitigation practices, such as climate-smart agriculture (CSA), which uses a range of climate-smart practices to address climate change adaptation and mitigation simultaneously	Seeks to achieve adaptation and mitigation objectives and outcomes, but there is a need to maximise synergies and minimise trade-offs between them

Source: Own elaboration.

3.1 Adaptation strategies

3.1.1 Crop improvement

Crop improvement consists of increasing the compatibility of crop biology with current and projected climates, with and without genetic improvement (Gao et al., 2023). In this regard, farmers tend to adjust the cropping calendar (sowing and harvesting dates) and change some cropping practices (e.g. planting density) and use varieties that are resistant to adverse perturbations (Jatav, 2024; Li et al., 2015; Makowski et al., 2020; Onyimadu, 2023). Novel crop varieties that can withstand different environmental stresses (drought, salinity, flooding, disease) will be essential to reduce risks and maintain productivity under climate change. This poses significant challenges for innovation to increase genetic gain rates, despite the importance of most current breeding priorities (Pixley et al., 2023). Combining phenomics and genomics with the use of innovative technologies for efficient database management could accelerate the development of climate-resilient crops (Benitez-Alfonso et al., 2023). Other measures include relocating agricultural production to more suitable areas and/or identifying the most productive crops in each area under current and future climates (Gao et al., 2023).

3.1.2 Improved water use and management

Irrigation under certain conditions (water availability) is considered a useful strategy to cope with drought stress (Li and Troy, 2018). However, this strategy is limited by several constraints, such as energy use and associated GHG emissions (Driscoll et al., 2024), as well as increasing long-term conflicts over water use (Grantham and Viers, 2014; Makowski et al., 2020). Improved water management can come from water-saving technologies for irrigation (drip, sprinkler and micro-irrigation, etc.) (Mi et al., 2021; Sengupta et al., 2023; Yang et al., 2023; Zhang et al., 2024), deficit and precision irrigation (Benzaouia et al., 2023; El Jaouhari et al., 2018; Saitta et al., 2021) and water harvesting systems (Carpio-Vallejo et al., 2024; Lin et al., 2019; Sanches Fernandes et al., 2015). Other comprehensive strategies include the use of non-conventional water resources, such as the use of treated wastewater (Al-Karablieh et al., 2024; Hassan Farooq et al., 2023; Manganiello et al., 2024) and desalinated seawater for irrigation (Aznar-Sánchez et al., 2021; Martínez-Álvarez et al., 2023; Martínez-Alvarez et al., 2016). The latter could make a significant contribution to addressing water scarcity. However, the use of this resource poses significant agronomic and environmental challenges due to its chemical specificities and the high

energy consumption and emissions associated with its production and distribution (Ben Abdallah et al., 2023; Martínez-Álvarez et al., 2023). Improvements in some aspects of the use of these non-conventional resources for irrigation have been studied (Al-Karablieh et al., 2024; Ben Abdallah et al., 2023; Hassan Farooq et al., 2023; Martínez-Álvarez et al., 2023) and future research is needed along these lines.

3.1.3 Soil health management

This strategy includes the adoption of soil conservation practices such as no-till and/or minimum tillage and residue retention, and other techniques such as windbreaks. The benefits of these practices are well documented in the literature, including improved soil organic carbon, water use efficiency, soil macrofauna biodiversity, erosion control and increased crop productivity (Hashimi et al., 2023; Liu et al., 2024; Verma et al., 2024).

3.1.4 Diversification

Diversification is a more systemic strategy involving profound changes in agricultural systems (Makowski et al., 2020), including other relevant agro-ecological alternatives such as agroforestry systems, mixed crop-livestock systems, intercropping and crop rotation (Burgess et al., 2022; Jones et al., 2021; Quandt et al., 2023). These diversification methods can provide economic benefits by minimising input requirements and improving or stabilising yields, as well as having positive effects on biodiversity and other ecosystem services (Jones et al., 2021).

3.1.5 Other adaptation strategies

Additional measures address other aspects such as early warning of weather and natural disasters (Miah et al., 2021), harvest optimisation (Shamshiri et al., 2018), quality (Hassoun et al., 2023a), transparency (Singh and Sharma, 2023), and traceability (Feng et al., 2020).

3.2 Mitigation strategies

3.2.1 Soil carbon sequestration

One of the key strategies for mitigating GHG emissions in agricultural systems is to improve soil organic carbon (He et al., 2022; W. He et al., 2021; Yu et al., 2024). Agricultural

practices that positively affect soil organic carbon include no-till and/or minimum tillage, crop residue retention, and crop rotation (Das et al., 2022; Kiran et al., 2023; Kiran Kumara et al., 2020; Li et al., 2021; Yu et al., 2024), biochar for soil amendment (Das et al., 2022; E et al., 2024; Kiran et al., 2023), and integrated nutrient management (Han et al., 2016; Kiran et al., 2023; Padbhushan et al., 2021).

3.2.2 Reducing livestock emissions

The livestock sector accounts for 70% of agricultural GHG emissions, so minimising its emissions remains a key priority (Agriculture, Forestry and Other Land Uses., 2023; Alif et al., 2024). Mitigation options to reduce methane emissions range from improved diets and nutrition (Chiriacò and Valentini, 2021; Congio et al., 2021; Hristov et al., 2022) and the use of methane inhibitors (Chiriacò and Valentini, 2021) to animal husbandry (Congio et al., 2021; de Haas et al., 2021; González-Recio et al., 2020) and precision animal husbandry and feeding (Su et al., 2024; Tullo et al., 2019). Minimising emissions from manure management is related to effective application, storage and deposition, as well as valorisation through use for biogas production (Alif et al., 2024; Chiriacò and Valentini, 2021; Gerber et al., 2013; Yalcinkaya, 2024).

3.2.3 Sustainable use of agricultural inputs

Improving the use and application of agricultural inputs remains crucial to mitigate the environmental impacts of highly polluting inputs such as nitrogen fertilisers, fossil fuels and conventional pesticides. In this regard, mitigation strategies range from the adoption of organic (Squalli and Adamkiewicz, 2023) and integrated farming practices (Chiriacò and Valentini, 2021) to less energy-intensive practices (e.g. improved tillage) (Pratibha et al., 2019) and precision agriculture (Ershadi et al., 2020).

3.2.4 Land use change

This strategy aims to increase mitigation potential in specific areas, for example through afforestation or reforestation of unused or abandoned land, and by changing crop production systems in specific production areas, for example from annual crops to perennial tree crops (Chiriacò & Valentini, 2021; Chiti et al., 2018).

3.2.5 Other mitigation strategies

Other strategies are to promote agricultural systemsthat are generally considered more environmentally friendly than their conventional counterparts, such as organic systems (Ben Abdallah et al., 2023; Thamarai et al., 2024), integrated agriculture (Chiriacò and Valentini, 2021), mixed crop-livestock systems (Ben Abdallah et al., 2024), agroforestry systems (Dmuchowski et al., 2024) and vertical farming (Thamarai et al., 2024).

3.3 Adaptation and mitigation strategies

Integrated strategies, consisting of practices that enable agriculture to simultaneously adapt to and mitigate climate change, are essential to ensure food security without compromising environmental sustainability, and vice versa (Barbieri et al., 2024). Indeed, the benefits of some strategies that focus on either adaptation or mitigation alone may be offset by increased GHG emissions and/or reduced crop yields (Grados et al., 2024; He et al., 2022). For example, practices that increase soil organic carbon may also increase nitrous oxide emissions and affect crop yields (He et al., 2022; Lehman et al., 2017; Xia et al., 2018). In this sense, some authors have investigated the potential of practices to strike a balance between crop yields and GHG emissions (Huang et al., 2022; Quemada et al., 2020; Wang et al., 2018). For example, He et al. (2022) identified some crop rotations with full residue retention as an effective strategy to reduce GHGs and achieve high gross margin.

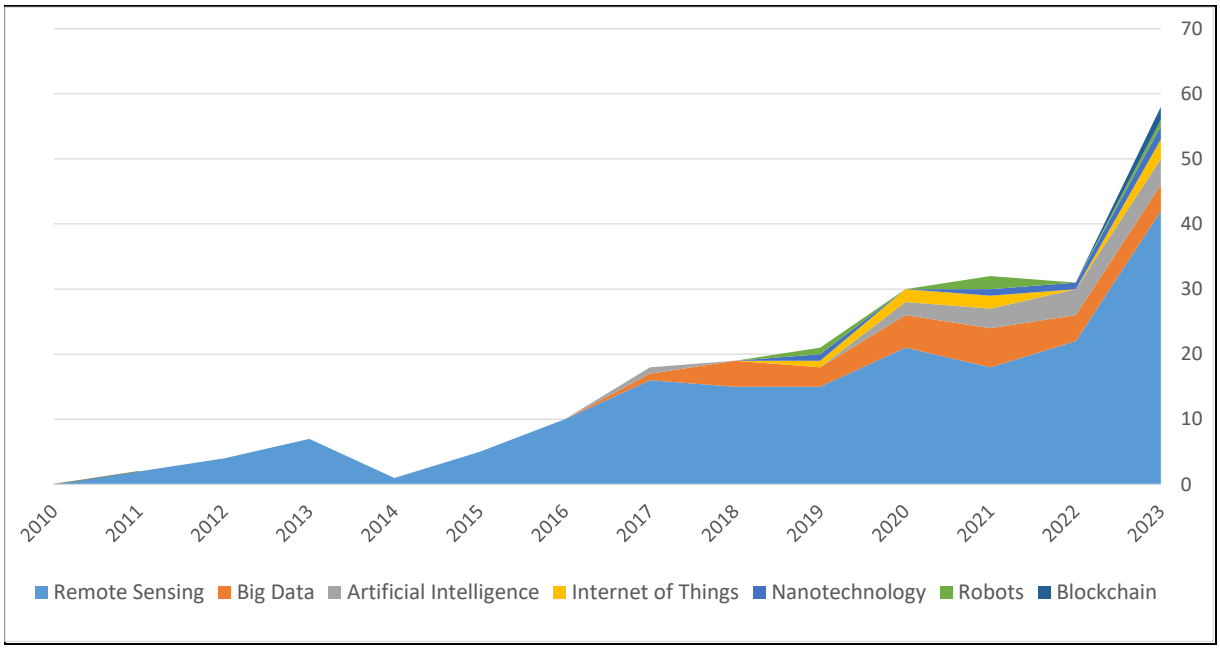
In this context, climate-smart agriculture (CSA) has emerged as an approach that aims to simultaneously achieve climate change adaptation and mitigation goals while maintaining agricultural productivity (FAO, 2013; Thottadi and Singh, 2024). CSA consists of applying a package of climate-smart practices, many of which have been mentioned above (see Thottadi & Singh, 2024). Studies on CSA have mainly focused on identifying and characterising CSA practices adopted by farmers in different regions (Naveen et al., 2024; Thottadi and Singh, 2024; Zheng et al., 2024). The main challenge facing CSA is to ensure a holistic approach that can effectively address the issues of GHG emissions and productivity (Ariani et al., 2018; McNunn et al., 2020; Thottadi and Singh, 2024).

4 Digital technologies in agriculture for climate change adaptation and mitigation

This section provides a comprehensive analysis of the different digital technologies used for climate change adaptation and mitigation in relevant case studies, providing a global perspective on the issue. It identifies unique challenges and tailored solutions within specific regional contexts. The main objective is to showcase the latest applications of digital technologies in different environmental and socio-economic landscapes. To this end, a literature review was conducted to identify recent studies and advances for a wide range of recognised digital technologies in the food chain (Hassoun, 2024). Again, the Web of Science and Scopus databases were searched for each digital technology using the following query (search in 'all fields'): (“climate change adaptation” OR “climate change mitigation” OR “climate change abatement”) AND (agricultur*) AND ([TECHNOLOGY]); where [TECHNOLOGY] = “artificial intelligence”; “big data”; “blockchain”; “internet of things”; “nanotech*”; “remote sens*”; and “robot*”. The references were then screened for their relevance to digital technologies, agriculture, and climate change adaptation and mitigation. In a few cases where few studies were found, the scope of the search was extended to include studies other than scientific articles published in academic journals.

Figure 2 shows the number of publications over time (in the Web of Science database only) for each of the different digital technologies identified in the review process. Although RS is currently the most prominent area of research, there is a clear increase in the exploration of BD and AI, indicating their growing importance. The steady figures for IoT and the lower but present figures for nanotechnology, robotics and blockchain indicate a diverse but targeted focus on digital technologies that can help address the multifaceted relationships between climate change and agriculture. The main findings of the review are discussed in the following sections.

Figure 2. Publications over time for different digital technologies in agriculture related to climate change adaptation/mitigation



Source: Own elaboration based on data from Web of Science.

4.1 Remote Sensing

RS refers to the process of gathering information about an object without touch or contact using airborne or satellite-based platforms equipped with various types of sensors operating in the optical, thermal and microwave spectral domains (Ullo and Sinha, 2021). The use of RS in agriculture has increased in recent years, revolutionising a wide range of agricultural tasks. It should be emphasised that the application of RS is closely related to other Agriculture 4.0 technologies, in particular AI, IoT, smart sensors, unmanned aerial vehicles (UAVs), geographic information systems (GIS) and wireless sensor networks (WSNs). RS is becoming increasingly important in facilitating the transition to the Agriculture 4.0 era. A recent review paper argues that remote sensors have a significant role to play in achieving the four cornerstones of Agriculture 4.0 (i.e. increasing production, enabling efficient resource allocation, addressing climate change adaptation and reducing food waste) through two proven applications, namely crop monitoring and yield forecasting (Mehedi et al., 2024).

A growing body of literature indicates that different types of UAVs are poised to revolutionise many aspects of precision agriculture, including vegetation growth and health, as well as irrigation and weed management (Istiak et al., 2023; Tsouros et al., 2019). For example, RS based on UAVs and a light detection and ranging (LiDAR) system was reported to be an effective technique for visualising the effect of windbreaks on wind erosion from field observations in a potato field (Iwasaki et al., 2024). Based on measurements of ridge height as an

indicator of the spatial distribution of wind erosion, the results showed the effectiveness of windbreaks in reducing this damage and ensuring optimal growing conditions. In particular, the combination of UAVs with WSNs, 5G and IoT enables energy-efficient data acquisition, leading to energy-saving, environmentally friendly and cost-effective solutions (Majumdar et al., 2023b). For example, the integration of WSNs with UAVs in an IoT framework has been proposed as a cost-effective solution for real-time intelligent data collection of various parameters such as temperature, humidity, soil moisture and water level (Singh and Sharma, 2022). Another application of RS techniques is in water management and climate change monitoring. For example, microwave and optical RS data have been used to monitor soil and vegetation water status in semi-arid areas of Tunisia and Egypt (Ramat et al., 2023). The results showed spatial and temporal variations in soil moisture and vegetation conditions over the years, highlighting a trend of increasing aridity in these Mediterranean regions.

Hyperspectral RS is one of the promising solutions being applied to perform various tasks in precision agriculture, such as predicting yield and crop quality, as well as calculating the dimensions of plant indices and soil nutrients, thus reducing the environmental impact of food production systems (Pande and Moharir, 2023). This is being achieved through the development of imaging platforms based on a range of airborne and spaceborne hyperspectral sensors, and the implementation of image processing and analysis techniques. This leads to promising specific agricultural applications such as estimation of soil moisture, fertility and other physical or chemical properties, biochemical and biophysical properties of crops, and image classification to identify many parameters related to crops, including crop nutrient status, species, growth stages, diseases, among others (Lu et al., 2020). For example, UAVs equipped with hyperspectral cameras can be used to monitor plant characteristics and map damage caused by extreme weather events such as hailstorms, as demonstrated by Furlanetto et al. (2024). In a similar study, a UAV hyperspectral imager combined with machine learning was used to provide a timely assessment of wheat nitrogen at the spatio-temporal scale (Sahoo et al., 2024). The results showed that the developed system was able to generate high resolution spatial and spectral data, allowing accurate prediction of different nitrogen levels in the leaves of wheat plants. Oliveira et al. (2023) investigated the utility of an unmanned airborne system using hyperspectral cameras operating in the visible-near-infrared and short-wave infrared spectral ranges to predict many qualitative and quantitative parameters of grass swards. Promising results were obtained, allowing the authors to recommend the use of such systems for various agricultural RS applications.

To improve the accuracy of results, data fusion has been proposed, which allows the combination of data from different sensors to obtain a wide range of information from different

sources (Omia et al., 2023). For example, the fusion of data (from UAVs, satellite images, GIS and others) has been proposed to optimise vineyard management and production parameters such as irrigation and fertilisation (Barrile et al., 2022).

4.2 Big Data

BD refers to the collection, storage, processing and analysis of large amounts of data from diverse and heterogeneous sources (Cravero et al., 2022). It has many applications in agriculture for climate change adaptation and mitigation, including crop, water, climate and soil management. The use of BD in agriculture can increase productivity through precision agriculture, data-driven agriculture, smart agriculture and predictive modelling (Sadiku et al., 2020). This can help respond to climate change.

BD predictive tools can help farmers plan for water shortages, droughts, heat waves, floods, increased and changing weed occurrence (Pasha and Reddy, 2024) and disease outbreaks by predicting outcomes such as weather conditions, pests and soil conditions (Luyckx and Reins, 2022), facilitated by digital platforms (Sarku et al., 2021). Researchers also advocate the use of BD genomics to identify, conserve and breed crop varieties adapted from wild relatives to increase crop adaptability and yields during heat waves and droughts (Cortés and López-Hernández, 2021; Gojon et al., 2022).

Anticipating the impacts of climate change is an important part of the adaptation strategy. Climate-smart agriculture enables adaptation to climate change by promoting the adoption of practices that enable crops, livestock and ecosystems to withstand extreme weather events (Konfo et al., 2024). Data-driven models that combine both model-based and sensor-based approaches can indicate the best approach, for example to detect water stress in orchards (Alizadeh et al., 2024). BD-enabled smart agriculture is helping farmers adapt rice production (Hashim et al., 2024; D. Li et al., 2022; Tiwari et al., 2024) and could support precision livestock management with the development of an industrial protocol for processing BD (Nyamuryekung'e, 2024).

Both crop and livestock models can be improved with better data, but it remains unclear whether such models can provide on-farm management recommendations or analysis of climate change impacts (Antle, 2019). A context-aware adaptive data cube framework based on Earth observation data has recently been proposed for efficient environmental monitoring for climate change mitigation (Temenos et al., 2024). This framework has the advantage of providing environmental monitoring tailored to the needs of a stakeholder without additional data processing.

Mitigating climate change from the agricultural sector requires transformation, which can be supported by predictive models informed by BD (Luyckx and Reins, 2022). Climate change mitigation involves implementing practices such as minimising emissions from livestock and machinery, regenerative agriculture to sequester carbon in soils and vegetation, and optimising land and water use to reduce soil degradation and deforestation (Konfo et al., 2024). It was found that digital innovations should be more closely linked to sustainability goals to prevent negative impacts such as rebound and displacement (Garske et al., 2021). Climate-smart agriculture using BD to inform at the farm level is fundamental to achieving these goals (Rao, 2017).

Big Data Analytics (BDA) can quickly analyse data to make predictions that can reduce GHG emissions. The adoption of climate-smart agricultural practices has significant mitigation potential in terms of GHG reductions and can be achieved through cost-saving options that benefit smallholder farmers (Sapkota et al., 2021). Data suggest that geographically targeted regenerative 'no-burn' rice residue management practices should be adopted to reduce GHG emissions (Cordeiro et al., 2024). Biochar produced from crop residues has the potential to be a negative emission technology, but computer-aided planning based on BD (e.g. from RS, GIS) is needed to maximise GHG emission reductions (Tan, 2019). It has been claimed that BD and AI have the potential to move the dairy industry towards net zero emissions (Neethirajan, 2024).

BDA can provide predictions to help manage soil resources. Soil organic carbon storage in semi-arid and arid regions has been found to be more sensitive to climate change, highlighting the need for BD to inform site-specific management practices (Hinge et al., 2021). As vegetation acts as a carbon sink, BD can be used to monitor and predict the impact of human activities on global vegetation productivity (Dang et al., 2024).

4.3 Artificial Intelligence

AI is generally understood as a system or set of systems that can exhibit intelligent behaviour by analysing its environment and making decisions with relative autonomy to achieve specific goals (Ryan et al., 2022). In this sense, the application of AI-based technologies offers significant opportunities to address climate change and its impacts. Although the development of these technologies in the agricultural sector is still at an early stage compared to other productive sectors such as energy or industry (Chen et al., 2023), there is already a large body of work incorporating AI into agriculture in various areas.

The application of AI to entomological research has received much attention in recent years. Several studies have used AI systems both to identify and track pests that can cause significant damage to crops and ecosystems (Chithambarathanu and Jeyakumar, 2023; Zhao et

al., 2022) and to develop predictive models that can forecast the spread of pest infestations and help prevent or mitigate their impact (Caselli and Petacchi, 2021; Chhetri et al., 2023). These advances are helping to reduce the overall use of pesticides and other chemicals, leading to a more sustainable and environmentally friendly approach (Hartbauer, 2024).

Advances in AI-based techniques are also being recognised in the field of weed management. Studies can be found using AI systems for weed detection (Espejo-Garcia et al., 2020; Kounalakis et al., 2019), weed classification (Raja et al., 2020) and weed control and treatment (Navas et al., 2020). The application of this technology reduces crop damage and agrochemical waste by eliminating randomness in fertiliser, herbicide and pesticide application, and increases food productivity by minimising GHG emissions to the atmosphere and reducing environmental impact (SaberiKamarposhti et al., 2024; Swaminathan et al., 2023).

Technological advances in genome sequencing and crop phenotyping, in parallel with rapid advances in computational techniques and data science methods, are leading to a revolution in biotechnology and plant breeding (van Dijk et al., 2021). The use of AI tools is enabling genomic and phenotypic analyses at scale and with precision, facilitating the rapid identification of key genes for desirable traits and the prediction of how genetic changes will affect plant traits (Joshi et al., 2024). These advances promise to greatly accelerate the development of new crop varieties that are resistant to pests and diseases and to changing and adverse climatic conditions such as high temperatures and drought (Sharma et al., 2023).

Water availability is one of the most important climatic conditions for agricultural production. In this area, AI is also driving significant innovations to optimise water use and increase irrigation efficiency (Patel et al., 2023). Research in this area has mainly focused on groundwater simulation and exploration (Chen et al., 2020), soil water content analysis (Song et al., 2016), evapotranspiration losses and their impacts (Kulisz et al., 2021), autonomous irrigation system design (Jha et al., 2019), agricultural drought tracking and monitoring (Shen et al., 2019), and farmer behaviour and irrigation community management (González Perea et al., 2019, 2018). AI-based technologies in this area not only help conserve valuable water resources, but also support environmental sustainability and climate change adaptation by improving the resilience of agricultural systems to climate variability and water scarcity.

Climate variability and water scarcity make climate prediction and management a critical task for agricultural management. To this end, AI-based technologies provide an opportunity by enabling more accurate and detailed climate models that can predict extreme conditions further in advance (Esteves et al., 2019; Poornima and Pushpalatha, 2019). This allows farmers to make informed decisions about when to plant, irrigate and harvest, minimising losses and better adapting to climate variability. In addition, integrating climate data with smart irrigation systems

optimises water use by adapting irrigation to actual crop needs based on predicted weather conditions (Talaviya et al., 2020).

Other areas of agriculture where AI tools are making important advances include harvesting and post-harvesting. AI is enabling the development of automated and selective harvesting systems that can identify the optimal ripeness of fruits and vegetables for harvesting, thereby ensuring quality and reducing waste (Chen et al., 2023; Zhou et al., 2022). At the post-harvest stage, advanced algorithms analyse and sort produce according to quality, size and other relevant parameters (Singh et al., 2022; Torres et al., 2019). This not only improves efficiency and minimises losses, but also ensures more effective distribution, contributing to the sustainability of the entire food system and reducing the environmental impact associated with food waste.

AI applications are based on mathematical developments such as classical neural network techniques and architectures such as CNN (Convolutional Neural Networks) or other multivariate analysis techniques. Many applications use existing large-scale models such as AlexNet, VGG16 or Inception-ResNet, while others develop their own CNN-based models. In the field of prediction, most models are based on MLP (Multilayer Perceptron Networks) or LSTM (Long-Short Term Memory), but more and more studies are exploring the possibilities of combining these models with other techniques such as logistic regression, Support Vector Machine (SVM), genetic algorithms, Bayesian methods, fuzzy logic, high margin classifiers, macroscopic cellular automata or digital twins (Liakos et al., 2018; Oliveira and Silva, 2023; Verdouw et al., 2021).

4.4 Internet of Things

IoT is emerging as a powerful tool in the fight against climate change. IoT-connected devices such as sensors can collect a wealth of data on soil moisture, weather patterns and fertiliser levels, enabling farmers to optimise irrigation practices and increase the efficiency of crop production (Dhanaraju et al., 2022). Automated farm machinery, including precision tractors, streamline essential tasks such as drilling, seeding and pesticide application, minimising reliance on manual labour and maximising resource utilisation. The IoT represents a sophisticated system of computing devices, mechanical components and digital machines, all equipped with unique identifiers (UIDs) (Grieve et al., 2019). This interconnected network can facilitate seamless data transfer without direct human intervention (Grieve et al., 2019).

The use of IoT in agriculture enables automated monitoring of crops, precision control of fertilisation and irrigation systems, and proactive management of pest and disease outbreaks, ultimately facilitating improved farm productivity (Zhang and Wang, 2024). Furthermore, IoT-

enabled solutions extend beyond the farm gate, contributing to broader environmental monitoring and conservation efforts. Farmers can use IoT devices to detect and report illegal deforestation activities, while also implementing early warning systems for natural disasters such as floods (Miah et al., 2021). Sensors strategically placed in river basins facilitate the collection of real-time data on critical flood parameters such as river flow, water levels, rainfall and wind direction, improving flood forecasting capabilities and strengthening resilience to climate-related challenges. The following paragraphs describe these techniques in more detail.

Traditional weed management techniques often rely on herbicides, which can have harmful effects on human health and the environment. Using IoT, novel approaches to weed detection and selective herbicide application have been proposed. Robots equipped with IoT sensors can detect and classify plants, enabling precise herbicide application only where needed. This not only reduces herbicide use, but also promotes human health and environmental sustainability (Dankhara et al., 2019).

Assessing soil quality is critical for effective agricultural planning and management. IoT-based systems use sensors and data analytics to assess soil characteristics and determine the suitability of land for different crops and irrigation systems. By automating the process of assessing land suitability, IoT solutions enable more informed decision-making, saving farmers time, money and labour (Mohammad El-Basioni and Abd El-Kader, 2024).

In addition, IoT-enabled smart agriculture is addressing the growing global demand for food while optimising the use of resources. IoT-enabled smart irrigation systems, coupled with energy management solutions, improve energy efficiency and reduce water consumption in agriculture. Innovative algorithms optimise cluster head formation and routing paths, resulting in significant energy savings and extended network life (Khan et al., 2022).

In addition, traditional weather monitoring systems often suffer from delays and inaccuracies, posing risks to agriculture. IoT-based weather monitoring systems collect real-time data from sensors and internet-connected weather stations, enabling accurate and timely weather forecasts. Integrated with various data sources, including satellite imagery and drones, IoT solutions provide accurate insights to stakeholders, facilitating informed decision-making in agriculture (Nabil et al., 2019).

Finally, forests play a critical role in mitigating climate change, yet deforestation remains a pressing issue. IoT-based forest monitoring systems use sensors and microcontrollers to detect unauthorised activities such as deforestation, fires, landslides and smoke. The data collected by these sensors is transmitted to the relevant authorities in real time, enabling prompt intervention to prevent environmental degradation (Sanli, 2023).

4.5 Nanotechnology

In agriculture, nanotechnology has been used to reduce the size of biochar particles to produce nanomaterials with enhanced physical properties and biological efficacy for application to soils (Ramanayaka et al., 2020). This nanochar has been shown to increase carbon sequestration and reduce methane and nitrous oxide emissions from agriculture, thereby contributing to climate change mitigation (Sani et al., 2023). Biochar can be produced by pyrolysis of lignocellulosic biomass and then used to produce nanostructures, for example through an ultrasonic bath sonication process (Pusceddu et al., 2019).

In addition, microorganisms can be used as economically and environmentally sustainable nanofactories to produce metal nanoparticles. The use of microorganisms such as bacteria, fungi, yeasts, actinomycetes and microalgae for the synthesis of nanoparticles offers unique opportunities in agriculture to support adaptation to climate change. For example, they can be used to produce nanofertilisers and nanopesticides that allow controlled release of active ingredients (Abdel-Aziz et al., 2023). Indeed, nanofertilisers have already been shown to increase nutrient use efficiency and plant tolerance to biotic and abiotic stresses, with significant benefits for sustainable agriculture and climate change mitigation (Babu et al., 2022). A notable example is the use of nickel-encapsulated nanoparticles with different biodegradable coatings to improve the physical properties of conventional nitrogen fertilisers (Beig et al., 2023). Finally, nanotechnological innovations have been proposed to perform artificial photosynthesis in food systems to mitigate climate change (Faunce and Bruce, 2017).

4.6 Robots

Robots are widely used in some industries, such as the automotive industry. In agriculture, robots are not as widely used, mainly because of their high cost. However, there are several applications of robots in agriculture that can contribute to climate change mitigation. The reduction of GHG emissions in agriculture through the use of robots has already been demonstrated (Y. Li et al., 2022). In particular, the use of robots for targeted spraying can reduce the application of pesticides and fertilisers, thereby reducing emissions as well as material costs, human labour and medical hazards (Adamides, 2020). This is important because the use of these chemicals has a large environmental impact.

Other applications of robots in agriculture include harvesting (Shamshiri et al., 2018), weed control (Birthisel et al., 2021), and detecting diseased crops in large agricultural fields for

rapid treatment (Grieve et al., 2019). Robots can also be programmed with AI and used for pest control and sensory data collection (Lubag et al., 2023).

4.7 Blockchain

Blockchain is a distributed ledger technology that records transactions on multiple computers connected through a peer-to-peer network (KPMG, 2021). Each block consists of a record that contains information about the previous block. The main benefit of using blockchain is to record and maintain a digital history of transactions with enhanced immutability, transparency and traceability (Budhi, 2022). The use of blockchain in the food sector has been explored, for example, to improve quality control (Hassoun et al., 2023a), security (Antonucci et al., 2019), transparency (Singh and Sharma, 2023), traceability (Feng et al., 2020) and efficiency (Duan et al., 2020).

In the agricultural sector, several studies have reviewed the main applications of blockchain (Dey and Shekhawat, 2021; Sajja et al., 2023; Xiong et al., 2020). The study by Lubag et al. (2023) states that 4.0 technologies, such as blockchain, can mitigate climate change if applied on a global scale by optimising agricultural performance. Vilkov and Tian (2023) explored the use of blockchain in carbon markets. They highlighted the applicability of blockchain in carbon offset projects, especially for carbon leakage, such as the displacement of indigenous communities' agriculture by large reforestation plantations. Therefore, blockchain can be used to study the climate change impacts of land use change in agricultural activities. Vilkov and Tian (2023) note that there is a lack of research on the use of blockchain in carbon offset projects in the agricultural sector.

Similarly, Bogart (2021) concludes that blockchain can be used to mitigate climate change by reducing deforestation, improving soil and nutrient management, and reducing livestock emissions. To reduce deforestation, smart contracts can be used to encourage farmers to conserve nature. Blockchain can help improve soil and nutrient management by optimising the management of arable and pasture land. Elsewhere, consumer demand for greener products can encourage farmers to market low-carbon livestock. In all cases, improved transparency and auditability through the use of blockchain can further mitigate the effects of climate change.

FAO and Wageningen University have published a detailed study describing the applications of blockchain in agriculture for climate change adaptation and mitigation, with several successful examples (Van Wassenaer et al., 2021). They argue that through climate finance, blockchain can support climate change adaptation techniques by opening up new value chains and platforms for smallholder farmers, such as rural credit through tokens, crowdfunding,

crowd lending and microinsurance. It can also support the monitoring of investments and the results of improved management techniques for climate change adaptation. For climate change mitigation, blockchain can help establish a global carbon data community to facilitate improved monitoring and evaluation of climate change mitigation efforts, as well as support the growth of the carbon market.

5 Concluding remarks: Challenges and opportunities

The convergence of digital technologies and agriculture offers a transformative approach to addressing the intertwined challenges of climate change and global food security. This section builds on the findings of the review and draws on insights from related literature to highlight significant advances and the evolving role of digital innovation in climate change adaptation and mitigation.

5.1 The digitalisation of agriculture and its relationship with climate change

Digital technologies have become a cornerstone of agricultural modernisation, providing tools for precision agriculture, improved water management and better crop monitoring and forecasting. These technologies enable real-time, data-driven decision-making, which is critical for optimising resource use and reducing the environmental footprint of agricultural practices (Balafoutis et al., 2017; Majumdar et al., 2023c, 2023a). Furthermore, the ability of digital solutions to facilitate carbon sequestration and reduce GHG emissions is an essential contribution to global climate change mitigation efforts (Bai et al., 2019; Tzilivakis et al., 2014). The potential of RS and AI to improve the resilience of agricultural production systems has been recognised (Jung et al., 2021).

The review conducted confirms that the digitalisation of agriculture is a transformative process in which digital technologies can be integrated into agricultural practices to improve productivity, efficiency and sustainability. This transformation plays a crucial role in addressing the challenges posed by climate change. Table 2 provides a summary visualisation of some of the findings, which are discussed in more detail below. Each digital technology is linked to its applications for both climate change adaptation and mitigation. For each application, its correspondence to the different adaptation/mitigation strategies defined in the previous section is indicated. Finally, the main contributions of each application to climate change adaptation/mitigation are highlighted.

708 **Table 2. Applications of digital technologies in agriculture and their impact on climate change adaptation and mitigation**

Digital technology	Applications	Correspondence with adaptation/mitigation strategies*	Key adaptation/mitigation contributions
Remote Sensing	Crop monitoring	Crop improvement; Sustainable use of agricultural inputs	Increases crop resilience, stabilises yields, facilitates precise and sustainable management of inputs and resources
	Yield forecasting	Crop improvement; Sustainable use of agricultural inputs	Improves yield forecasting, reduces risks, enables better decisions input use and application
	Visualisation of windbreak effectiveness	Soil health management	Optimises crop protection against erosion, increases water use efficiency and effectiveness of other practices
	Intelligent real-time data collection (integrated with other digital technologies)	Sustainable use of agricultural inputs; Soil health management; Improved water use and management	Enables efficient data-driven farm management, improves agricultural practices
	Water management and climate change monitoring	Improved water use and management; Other adaptation strategies	Supports water management, monitors environmental trends
Big Data	Predictive modelling of water shortages and pest outbreaks	Improved water use and management; Sustainable use of agricultural inputs	Optimises resource use, facilitates precision agriculture
	Big Data genomics	Crop improvement	Improves crop resilience through genetic adaptation
	Data-driven detection of water stress in orchards	Improved water use and management	Detects early signs of water stress, improves water management
	Predictive modelling for environmental monitoring	Integrated strategies	Tailors environmental monitoring to needs, reduces emissions
	Regenerative 'no-burn' management of rice residues	Soil health management; Soil carbon sequestration	Reduces GHG emissions through improved residue management
	Soil resource management	Sustainable use of agricultural inputs; Soil health management	Reduces environmental impact, improves soil management
Artificial Intelligence	Pest identification and tracking	Sustainable use of agricultural inputs	Reduces pesticide use, improves environmental sustainability
	Weed management	Sustainable use of agricultural inputs	Minimises herbicide use, reduces environmental impact
	Genomic and phenotypic analysis for crop breeding	Crop improvement	Accelerates breeding of climate-resilient crops
	Water use optimisation and irrigation efficiency	Improved water use and management	Optimises irrigation, saves water
	Climate forecasting and management	Other adaptation strategies	Improves accuracy of climate models, improves farm decision-making
Internet of Things	Automated crop monitoring	Crop improvement; Sustainable use of agricultural inputs	Improves crop monitoring, increases yield stability

	Precision fertiliser management	Sustainable use of agricultural inputs	Reduces fertiliser waste, reduces environmental impact
	Natural disaster early warning	Other adaptation strategies	Improves disaster response, increases resilience
	Soil quality assessment	Soil health management	Improves land suitability assessments, informs better crop placement
	Weather monitoring systems	Other adaptation strategies	Provides real-time weather data, supports precision agriculture
	Forest monitoring systems	Diversification; Other mitigation strategies	Protects forests, maintains biodiversity and other ecosystem services
Nanotechno-logy	Production of nanochar for soil improvement	Soil carbon sequestration	Improves carbon sequestration, mitigates climate change
	Synthesis of nanofertilisers and nanopesticides	Sustainable use of agricultural inputs	Increases nutrient use efficiency, reduces emissions
Robots	Targeted spraying	Sustainable use of agricultural inputs	Reduces pesticide and fertiliser emissions, improves safety
	Automated harvesting	Other adaptation strategies	Ensures optimal harvest timing, minimises waste
	Disease detection in crops	Crop improvement; Sustainable use of agricultural inputs	Accelerates detection and treatment, improves plant health
Blockchain	Soil improvement and nutrient management	Soil health management; Sustainable use of agricultural inputs	Optimises land management, reduces environmental impact
	Improving the quality, transparency and traceability of food production	Other adaptation strategies	Improves food quality, supply chain transparency, supports sustainable practices
	Monitoring carbon offset projects	Other mitigation strategies	Facilitates carbon trading, supports climate change mitigation

*Source: Own elaboration. * See Table 1.*

5.1.1 Remote Sensing and Big Data: Improving decision making and resource management

RS and BD technologies are emerging as powerful tools for improving agricultural practices and environmental monitoring. These technologies facilitate crop monitoring, yield forecasting and real-time intelligent data collection that directly address adaptation strategies, such as crop improvement, and mitigation strategies, such as sustainable use of agricultural inputs. By providing farmers with accurate and timely information, these technologies enable data-driven decisions that can increase crop resilience, stabilise yields and optimise resource use.

In addition, BD applications extend beyond farm-level management to broader environmental issues. Predictive modelling for water scarcity, pest outbreaks and environmental monitoring demonstrate the potential of these technologies to address complex, large-scale challenges associated with climate change. The use of BD in genomics further illustrates its potential to improve crop resilience through genetic adaptation, a critical aspect of long-term adaptation to climate change.

5.1.2 Artificial Intelligence and the Internet of Things: Precision and automation in agriculture

AI and IoT are the next frontier for precision agriculture. AI applications such as pest identification, weed management and genomic analysis for crop breeding directly contribute to sustainable input use and crop improvement strategies. These technologies not only reduce the environmental impact of agricultural practices, but also accelerate the development of climate-resilient crops.

IoT complements AI by providing a network of sensors and automated systems for real-time monitoring and management. Applications ranging from automated crop monitoring to precision fertiliser management and early warning systems for natural disasters demonstrate how IoT can enhance both adaptation and mitigation efforts. By enabling more precise and timely interventions, these technologies can significantly reduce waste and emissions associated with agricultural inputs, while improving overall farm resilience.

5.1.3 Nanotechnology, Robotics and Blockchain: Emerging technologies

Table 2 also highlights emerging technologies that show promise in addressing specific aspects of climate change adaptation and mitigation in agriculture. Nanotechnology, for

example, offers innovative solutions for soil improvement and more efficient use of agricultural inputs, directly contributing to soil carbon sequestration and reduced emissions.

Robotics in agriculture offer opportunities for more precise and efficient farming, from targeted spraying to automated harvesting and disease detection. These applications can significantly reduce the use of pesticides and fertilisers, thereby reducing agricultural emissions while improving crop health and yield stability.

Blockchain technology can play a crucial role in improving the transparency and traceability of food production. This can indirectly support climate change mitigation efforts by facilitating carbon offset projects and adaptation strategies, by promoting transparency and quality throughout the agricultural supply chain.

5.1.4 Integrated approach to climate change adaptation and mitigation

A key insight from the analysis is the multifaceted nature of digital technology contributions to climate change adaptation and mitigation in agriculture. Many technologies and applications address multiple adaptation and mitigation strategies simultaneously. For example, RS technologies contribute to crop improvement, sustainable use of agricultural inputs, soil health management and improved water use management. This integrated approach is essential to address the complex challenges of climate change. By leveraging digital technologies, the agricultural sector can pursue a holistic strategy that builds resilience to climate impacts while reducing its environmental footprint.

5.2 Challenges ahead

In pursuing the integration of digital technologies for climate change adaptation and mitigation in agriculture, several challenges need to be addressed in order to achieve effective implementation and maximise potential benefits. Key barriers include issues of digital divide, affordability and accessibility (Anastasiadis et al., 2018; Jamil, 2021; Mehrabi et al., 2021). Indeed, one of the main challenges is the digital divide, which limits access to necessary technologies in rural and underdeveloped regions and requires significant investment in infrastructure and training (Samadder et al., 2023). High upfront costs often hinder adoption by smallholder and resource-poor farmers, highlighting the need for financial incentives such as grants and low-interest loans (Sheik, 2023). The complexity of digital tools can make them difficult to use, especially for less tech-savvy populations. This highlights the need to simplify user interfaces and provide comprehensive support (Marshall et al., 2022).

In addition, privacy and security concerns arise as agriculture becomes increasingly data-driven, requiring the implementation of robust data governance frameworks (Jouanjean et al., 2020). The integration of advanced digital technologies with traditional farming practices also presents challenges, particularly in culturally rooted regions, and requires the development of tailored solutions that take into account local contexts (Sheikh and Berenyi, 2023). In addition, there are environmental and sustainability concerns about the significant water and energy consumption, CO2 emissions and e-waste generation associated with digital technologies (Samuel et al., 2022).

In the specific case of RS, despite its merits in the context of Agriculture 4.0, there are a number of challenges, mainly related to the complexity of the data and the need for skilled professionals to handle such a large amount of data. Therefore, a new vision, Agriculture 5.0, has been proposed in recent years to overcome the challenges of Agriculture 4.0 and improve human welfare, resource management and decision making (Victor et al., 2024).

Otherwise, the implementation of BD applications requires a multidisciplinary approach (del Pozo et al., 2019) and a system-of-systems perspective (Sebestyén et al., 2021) to develop context-specific strategies for climate change adaptation and mitigation. A major concern with large climate change data is how to store, process and analyse the very large amounts of data, which is challenging for current algorithms (Cravero et al., 2020; Ikegwu et al., 2024). The European Commission aims to establish European data pools to enable BD analysis. This needs to be done in a clear, fair and workable way that respects privacy and competition law (Garske et al., 2021).

Furthermore, the application of AI techniques in the agricultural sector still has much room for improvement and great potential for further development, especially when combined with other technologies such as BD, IoT or RS, among others (Misra et al., 2022). The synergies that can be created between these technologies extend the capabilities of each of them individually and open up new opportunities to seek more sophisticated, personalised and efficient solutions that respond to the major challenges facing the agricultural sector.

In the case of robotic applications, such as milking robots in the dairy industry, Burton and Farstad (2020) point out that their use can push farmers towards intensification, leading to higher emissions. Furthermore, the widespread development of robotic solutions in agriculture faces several challenges, such as technological complexity, high economic investment, need for adaptation and training of farmers, lack of standardised solutions and potential reduction in demand for manual labour (Sharma et al., 2024).

5.3 Future opportunities

Identifying opportunities to integrate digital technologies into agriculture can significantly increase the resilience and productivity of agricultural systems while minimising their environmental impact, thereby contributing to global climate change mitigation efforts. Expanding access to digital technologies, particularly in developing countries, is a key area for future development. This includes improving infrastructure, reducing costs and increasing digital literacy among farmers (Adenle et al., 2015; Balasundram et al., 2023). In addition, technologies such as blockchain and advanced AI algorithms can be further integrated into agricultural systems to improve traceability, enhance supply chain management and optimise resource use. This could lead to improved sustainability practices and greater transparency in agricultural processes (Loboguerrero et al., 2019).

In addition, the development of more sophisticated data analysis tools and AI models can provide deeper insights into climate risks and adaptation needs. These tools can predict environmental changes and their potential impacts on agriculture, allowing for pre-emptive action (Gupta et al., 2023; Luyckx and Reins, 2022). In addition, the increased use of autonomous robots for tasks such as planting, harvesting and weeding can reduce labour costs and environmental impacts (Sivasangari et al., 2023). Advances in robotics could facilitate the implementation of more precise and efficient agricultural practices, thereby reducing the use of resources such as water and pesticides (Balaska et al., 2023; Cheng et al., 2023; Oliveira et al., 2021).

There are also opportunities to scale up the adoption of climate-smart agricultural practices that make use of digital technologies. This includes promoting synergies between adaptation and mitigation strategies to maximise the benefits of both (Makate, 2019; Westermann et al., 2018). In addition, the development of advanced monitoring systems that can detect and respond to climate impacts in real time is critical. This can be achieved through the use of IoT devices that provide continuous data streams, enabling dynamic responses to climate anomalies (Laha et al., 2022). By providing real-time data and actionable insights, IoT solutions enable farmers to optimise resource use, increase productivity and minimise environmental impacts.

5.4 Research directions

To address the challenges and opportunities identified, future research needs to focus on several key areas. It is crucial to adapt digital solutions to local agricultural contexts (Mabaya and Porciello, 2022). It is also important to explore the integration of multiple technologies, such as RS, IoT and AI, to optimise resource use and improve smart agriculture (Adenle et al., 2015; Balasundram et al., 2023; Basso and Antle, 2020; Inoue, 2020; Sishodia et al., 2020; Ullo and Sinha, 2021). Research should focus on scalable and accessible solutions for all farmers, including the development of digital diagnostic tools for agricultural cooperatives to support their decision-making processes (Ciruela-Lorenzo et al., 2020). The use of digital technologies in agriculture is often associated with high costs, which can be a barrier for smallholder farmers (Sheik, 2023). In addition, climate change adaptation and mitigation is a global issue that requires collective action for sustainability. Balancing these interests is critical. Digital technologies can improve productivity and resilience, but need to be economically viable. Research is needed on the design of incentive mechanisms, such as subsidies and grants, that can reduce financial burdens and encourage technology adoption, thereby supporting both economic development and environmental protection.

Otherwise, to address the potential contribution of digital technologies to energy consumption, CO2 emissions and e-waste generation, future research should focus on developing energy-efficient devices and integrating renewable and green energy sources to reduce carbon footprints (Palniladevi et al., 2023), conducting comprehensive life cycle assessments (LCA) to identify and mitigate environmental impacts (Acosta-Alba et al., 2019), implementing e-waste recycling programmes to promote material reuse and reduce environmental impacts (Samuel et al., 2022), and creating policies and financial incentives to support the adoption of green technologies in agriculture. In addition, improving data analysis capabilities, developing predictive models for climate adaptation, formulating supportive policies, and continuously monitoring impacts are essential. Digital agricultural policies need to be adapted to support the sustainability and effective use of digital tools (Ehlers et al., 2021).

The application of digital technology in agriculture extends beyond technical advances to important socio-economic dimensions. A key issue is the digital divide, which can lead to technological inequality, where the benefits of digital agriculture are unevenly distributed across different socio-economic groups. Globally, there are significant differences between developed and developing countries. While developed countries tend to adopt more advanced, technology-driven adaptation and mitigation strategies based on digital technologies, such as AI for genomic and phenotypic analysis and robotics to reduce water and pesticide use (Balaska et al., 2023; Cheng et al., 2023; Oliveira et al., 2021), developing countries focus on practical, cost-effective solutions that are feasible within their resource constraints (Jatav, 2024; Li et al., 2015; Makowski

et al., 2020; Onyimadu, 2023). This distinction highlights the need for tailored approaches that take into account the specific technological, economic and socio-political contexts of different regions. Research should focus on exploring technology transfer and adaptation, capacity building and education. This could include the development of affordable, simplified versions of advanced technologies and training programmes for local farmers. Collaborative frameworks and international partnerships can facilitate knowledge sharing and resource allocation. In addition, cost-effective innovations, policy interventions, localised solutions tailored to specific regions and sustainable financing models such as microfinance and international grants can be crucial. Integrated approaches that combine traditional and modern practices can also create resilient and sustainable agricultural systems.

Within countries, technological inequality and the digital divide can be influenced by factors such as income, education and geographic location (Oke and Cordelia, 2022; Rotz et al., 2019). Wealthier farmers or those in urban areas are more likely to benefit from technological advances, including digital tools, than poorer or rural counterparts (Mesquita et al., 2021; Wang et al., 2023). Technological inequality can lead to a concentration of benefits among a small group of technologically savvy and high-income farmers, while others are left behind, perpetuating a cycle of poverty and limited opportunities. Research should focus on assessing digital literacy and access and developing targeted technology solutions. Tailored training programmes and policy interventions can improve equitable access. Localised solutions, including community-led initiatives and gender-specific strategies, can ensure greater inclusivity. Longitudinal studies of technology adoption and the role of local governments in bridging the digital divide are also needed. Collaborative knowledge-sharing networks can foster innovation and resilience across socio-economic groups.

Otherwise, according to Barbieri et al. (2024), most studies on the potential of agricultural practices to achieve synergistic outcomes between climate change adaptation and mitigation are based on secondary data rather than empirical assessments. Therefore, a large body of substantial work and evidence is needed with robust assessment tools and spatio-temporal datasets on the adaptation and mitigation outcomes of agricultural practices and strategies, as well as potential synergies and trade-offs (Barbieri et al., 2024; Chemura et al., 2024). In this sense, the emergence of innovative concepts such as precision agriculture and smart farming through the use of digital technologies can help maximise synergies between adaptation and mitigation outcomes of agricultural practices, which is crucial to effectively address climate change (Makate, 2019; Westermann et al., 2018).

Understanding the human-technology interface, ethical considerations and managing employment impacts will also provide deeper insights into improving the adoption and

effectiveness of digital technologies in agriculture. In addition, it is crucial to explore the potential of Agriculture 5.0, a concept that builds on the innovations of Agriculture 4.0 to create smarter and more efficient agricultural systems that are highly automated and data-driven. These systems will address broader sustainability challenges and improve environmental stewardship (Balaska et al., 2023). These combined efforts will ensure that digital advances contribute significantly to sustainability, climate resilience and social equity in the agricultural sector.

As a summary of the results obtained, and going further into the details of each digital technology, Table 3 provides a comprehensive overview of how these technologies contribute to climate change and mitigation, barriers to implementation, opportunities and areas where further research and development is needed.

930 **Table 3. Contributions, challenges, opportunities and research directions for digital technologies in agriculture**

Digital technology	Contributions to climate change and mitigation	Challenges	Opportunities	Research directions
Remote Sensing	Increases crop resilience and yield stability; Enables precise and sustainable management of inputs and resources; Improves yield forecasting and risk reduction; Optimises crop protection against erosion; Improves water use efficiency; Facilitates data-driven farm management; Supports environmental trend monitoring	Complexity of data requires skilled professionals; Digital divide limits access in rural and underdeveloped regions	Expand access, especially in developing countries; improve infrastructure and reduce costs; Increase digital literacy of farmers	Adapt solutions to local agricultural contexts; Develop simplified, accessible solutions; Integrate with other technologies (IoT, AI) to optimise resource use; Develop supportive policies
Big Data	Optimises resource use and facilitates precision agriculture; Improves crop resilience through genetic adaptation; Improves water management and early stress detection; Tailors environmental monitoring to specific needs; Reduces greenhouse gas emissions through improved residue management; Minimises environmental impact and improves soil management	Storage, processing and analysis of large amounts of data is challenging; Requires multidisciplinary approach and system-of-systems perspective; Privacy and data governance concerns; High up-front costs hinder adoption by smallholders	Develop more sophisticated analytics and AI models for climate risk insights; Scale up adoption of data-driven, climate-smart practices; Predict environmental changes and impacts for pre-emptive action	Improve data analysis capabilities; Develop predictive models for climate adaptation; Establish data pools with clear governance
Artificial Intelligence	Reduces pesticide and herbicide use; Improves environmental sustainability; Accelerates breeding of climate-resilient crops; Optimises irrigation and water conservation; Improves accuracy of climate models and farm decision-making	Still much room for improvement, especially when combined with other technologies; Complexity makes it difficult to use by less tech-savvy farmers; Requires tailored solutions that consider local contexts	Integrate advanced AI algorithms to optimise resource use; Integrate with agricultural systems to improve traceability and sustainability practices; Provide deeper insights into climate risks and adaptation needs	Explore AI integration with BD, IoT, remote sensors for advanced personalised solutions; Simplify user interfaces and provide comprehensive support; Conduct life cycle assessments to identify and mitigate environmental impacts
Internet of Things	Improves crop monitoring and yield stability; Reduces fertiliser waste and environmental impact; Improves	Privacy and security concerns require robust data governance; Integration with	Develop advanced monitoring to detect and respond to climate impacts in real time;	Design incentives for equitable adoption; Simplify interfaces; Provide robust support

	disaster response and resilience; Improves land suitability assessment and crop placement; Supports precision agriculture with real-time weather data; Protects forests and maintains biodiversity	traditional farming poses cultural challenges; Collaboration between policymakers, researchers and farmers is essential to realise the full potential of IoT	Provide continuous data streams for dynamic response to anomalies	
Nanotechnology	Improves carbon sequestration and mitigates climate change; increases nutrient use efficiency and reduces emissions	Limited research on potential health and environmental risks; High production costs limit widespread adoption	Develop nanotech for soil improvement, efficient input delivery; Explore potential for emissions reduction; Develop tailored, affordable solutions for smallholder farmers in developing countries	Conduct comprehensive safety and environmental impact assessments; Develop affordable, scalable nanotech solutions; explore integration with other precision farming technologies
Robots	Reduces pesticide and fertiliser emissions; Improves farm safety; Ensures optimal harvest timing and minimises waste; Accelerates disease detection and treatment	Can push farmers towards intensification, leading to higher emissions; Technological complexity and high investment costs; Need for farmer adaptation and training; Lack of standardised solutions; Potential reduction in demand for manual labour	Develop autonomous robots for precise planting, harvesting and weeding to reduce costs and environmental impact; facilitate implementation of precise, efficient practices to reduce resource use	Assess impacts on labour and rural communities; Develop accessible, modular robotics; Establish standards and best practices; Explore models for robot sharing and service provision; Develop training programs
Blockchain	Optimises land management and reduces environmental impact; Improves food quality and supply chain transparency; Supports sustainable practices; Facilitates carbon trading and climate change mitigation	Requires significant digital infrastructure and literacy; Regulatory uncertainties and lack of standardisation; Scalability and throughput limitations	Integrate with IoT for automated, trusted data capture; Develop smart contracts for carbon trading	Develop energy-efficient consensus mechanisms; Establish regulatory frameworks and standards; Improve scalability and performance; Integrate with IoT for automated, transparent data collection

931 *Source: Own elaboration.*

5.5 Call to action

The convergence of technology and agriculture makes the need for concerted action more urgent than ever. The advent of rapid advances in digital technologies offers a unique opportunity to transform agricultural practices, making them more sustainable, efficient and resilient in the face of climate change (Basso and Antle, 2020). However, realising this potential requires a collaborative effort involving multiple stakeholders, including researchers, policymakers, technology developers and farmers (Balasundram et al., 2023). To facilitate the adoption of digital technologies in agriculture, policy makers should create an enabling environment through supportive policies and regulations. This should include providing incentives for technology development, ensuring equitable access to these innovations, and protecting data privacy and security (Ehlers et al., 2021). The effectiveness of digital technologies depends on robust infrastructure, skills development, policy support and a comprehensive governance framework to address privacy, security and ethical concerns (Bronson and Knezevic, 2016; Fabregas et al., 2023; Parra-López et al., 2024).

The effectiveness of both adaptation and mitigation practices depends on many factors, such as agro-climatic conditions, socio-economic contexts and farming systems, and may lead to different outcomes on a global scale (Hoegh-Guldberg et al., 2018; Kiran et al., 2023; Makowski et al., 2020). Indeed, such benefits could also be reduced due to weather extremes and the occurrence of pests and diseases (Makowski et al., 2020; Webber et al., 2018). Therefore, policy makers should provide useful information to farmers through effective weather forecasting systems and facilitate the dissemination of developed and advanced technologies (Li et al., 2015).

It is imperative that technology developers and industry leaders prioritise the development of accessible, cost-effective solutions that can be deployed at scale, especially in underserved regions (Adenle et al., 2015). Ensuring that these technologies are robust, user-friendly and tailored to farmers' needs is key to their success. It is therefore essential that farmers and farm workers, as the primary users of digital technologies, are involved in the development and implementation process. Providing them with the necessary training and resources to adopt and adapt these technologies will be crucial for their widespread adoption (Maria et al., 2021; Xie et al., 2021).

In summary, the integration of digital technologies in agriculture is a promising avenue for collective action in the context of climate change. It requires building bridges between different groups, fostering innovation and striving for a sustainable future.

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