CHAPTER 6

Smart Farming Technologies and Sustainability

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Abstract This chapter discusses how smart farming technologies are being used to optimise and transform agricultural practices and food systems to make them more sustainable and resilient to the climate change and food security crises. These include precision farming, water-smart, weather-smart, carbon, and energy-smart, as well as knowledge-smart agricultural practices. Adoption of these technologies comes with various barriers and drivers which hinder or aid farmers in their transition to

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digital agriculture. These are categorised into socio-demographic, psychological, farm characteristics, technology-related, systemic, and policy factors. The chapter also discusses international visions of future food systems based on digital technology promoted by international agencies such as the United Nations (UN) Food and Agriculture Organisation (FAO), the Organisation for Economic Co-operation and Development (OECD), and the World Bank as well as the European policy framework to support and monitor digitisation in agriculture and the food system.

Keyword Smart farming; technology adoption; policy

6.1 INTRODUCTION

Modern-day agriculture and the challenges it is currently facing are at the epicentre of international and European policy agendas. Climate change with its extreme and unpredictable weather patterns (e.g., extreme high and low temperatures, floods, and long dry periods) jeopardises food production causing a global food security crisis. Agriculture is expected to feed the rising global population which is estimated to reach 9.7 billion by 2050 increasing food demands by 50% (Kumar et al., 2022). At the same time, agriculture is a major cause of environmental degradation with its negative impacts on soil erosion, water use, water and air pollution, greenhouse gas (GHG) emissions, and biodiversity loss (Begho et al., 2022). Smart farming technologies promise to tackle these challenges by enabling optimisation of resource use, increased performance and productivity while creating sustainable production systems (Pathak et al., 2019). The modernisation and the digitalisation of the agricultural sector are a high priority at international and European levels. At an international level, agencies such as the United Nations (UN) Food and Agriculture Organisation (FAO), the Organisation for Economic Co-operation and Development (OECD), the World Bank as well as the European Union (EU), with its notable Green Deal, Farm-to-Fork strategy and Common Agricultural Policy (CAP), pave the way to the transition of food systems to digital agriculture. Despite the prominent benefits associated with the technologies and the policies that support the transformation of the agricultural sector, adoption of smart farming technologies remains slow and low. Various barriers hinder farmers and food systems from their transition to smart farming technologies. In order to foster transition, we need to understand farmer behaviour and integrate behavioural insights into policy design. This chapter aims to present the current trends, challenges, and policy agendas in the context of smart farming technologies and provide some recommendations for future research and policy.

The remainder of this chapter is structured as follows. Section 6.2 provides an overview of the existing smart farming technologies along with the evaluation of the benefits and costs associated with the environmental, economic, and social dimensions. Sections 6.3 and 6.4 outline the barriers and drivers for adoption of smart farming technologies and the policy framework at both international and European levels, respectively. Key regulations and initiatives are discussed with respect to their impact in the transition to digital agriculture. Section 6.5 concludes the chapter with some final remarks about smart farming and sustainability.

6.2 Smart Farming Technologies: Social, Environmental, and Economic Benefits

Smart farming is seen as a pivotal strategy for breaking away from conventional farming technologies and practices, offering an orchestrated path towards sustainable agriculture by achieving significant savings in crop inputs while maintaining or even increasing crop yield. This can benefit environmental protection resulting in less air, water, and soil pollution. Furthermore, smart farming contributes to food security and health protection while also maintaining the livelihoods of rural communities. As such, the adoption of smart farming technologies, including precision agriculture, water-smart, and carbon and energy-smart practices, coupled with knowledge-enhancement activities, is essential for realising a more sustainable, efficient, and socially responsible agricultural sector (Erickson & Fausti, 2021; Pathak et al., 2019). The rest of this section will explore the various smart farming technologies and methods, along with their associated benefits and costs, highlighting their potential to transform agriculture.

Precision Farming

Precision farming, also known as precision agriculture, encompasses a range of technologies and practices aimed at optimising various aspects of crop production, such as sowing, spraying, fertilisation, irrigation, and harvesting by optimising crop inputs which consequently lead to minimising environmental impact. Precision farming utilises many technologies, such as sensors, global navigation satellite systems (GNSS), robots, smart implements, Artificial Intelligence (AI), and Information and Communication Technologies (ICTs), which can be found in space, air, water, on ground, or below ground (Anastasiou et al., 2023b; Fountas et al., 2020; Liakos et al., 2018). By leveraging precision agriculture, farmers can make informed decisions leading to cost savings in relation to inputs (e.g., fertilisers, seeds, nutrients, power, and fuel), reduced waste, and more efficient workload management based on spatial and temporal variability and consequently needs (Anastasiou et al., 2023b; Fountas et al., 2020). Moreover, the social impact of precision farming is significant, as it plays a crucial role in ensuring a stable food supply and reducing health problems across the value chain (farmers, industry workers, and consumers) (Talebpour et al., 2015).

Water-Smart Agricultural Practices

Water-smart agricultural practices, such as rainwater harvesting and micro-irrigation, play a crucial role in sustainable water management, offering significant social, environmental, and economic benefits. These practices can use advanced technologies (e.g., automated actuators) and/or environmentally friendly approaches (e.g., rainwater harvesting, solar-powered irrigation, and aquifer recharge). These practices are essential for addressing the challenges associated with water availability, access, and use in agriculture, particularly in the context of a changing climate (Frimpong et al., 2023). Moreover, water-smart agricultural practices help reduce pressure on traditional water sources, and minimise soil erosion, enhance water-use efficiency, and reduce water waste from an environmental perspective. Economically, water-smart agricultural practices can lead to cost savings and improved productivity. By maximising crop yields per volume of water applied, these practices contribute to enhanced resource utilisation and overall profitability. In relation to the social aspect, water-smart agriculture plays a significant role in ensuring food security and supporting the livelihoods of farming communities due to increased production which results to higher economic profits and welfare (Patle et al., 2019).

Weather-Smart Practices

Weather-smart practices, such as ICT-based agro-meteorological services and index-based insurance, are essential components of smart farming technologies. These practices leverage weather data and analytics to support informed decision-making and risk management in agriculture. For example, these practices are used to inform farmers of pest infestations or crop phenological stages and therefore to proceed to pest control or other appropriate farming practices (e.g., fertilisation, tillage), respectively (Khatri-Chhetri et al., 2017). Moreover, weather-smart services play a significant role in crop insurance. Weather-based indices are used to determine crop yield loss and consequently loss in farm income due to extreme weather events (e.g., dry weather, heat waves, hail) (Dalhaus et al., 2018). From an environmental perspective, weather-smart activities contribute to sustainable resource management by optimising water use, reducing soil erosion, and minimising the use of chemicals and pesticides. Additionally, weather-smart activities can lead to cost savings and improved productivity by providing real-time weather information and enabling farmers to optimise their operations, reduce risks, and enhance overall profitability. In terms of social aspects, weather-smart activities play a crucial role in ensuring food security and supporting the livelihoods of farming communities due to the better information of farmers which can help them prevent and mitigate production related losses caused by advert weather conditions. Thus, by providing access to weather information and risk management tools, these activities contribute to sustainable food production and the resilience of agricultural systems (Khatri-Chhetri et al., 2017).

Carbon and Energy-Smart Practices

One other aspect to which smart farming technologies can contribute is related to carbon sequestration and energy consumption. Carbon and energy-smart practices in agriculture, such as zero-tillage and residue management, play a crucial role in mitigating climate change and promoting sustainable land use. More specifically, zero-tillage practice, enabled by smart farming technologies such as auto-guidance, minimises soil disturbance by reducing the number of times the soil is tilled, thereby retaining soil carbon, promoting soil health, increasing and decreasing fuel consumption (Javaid et al., 2022). Moreover, by incorporating crop residues into the soil, the soil organic matter is increased, resulting in soil moisture retention, and suppressed weed population. Another relevant practice is cover cropping. Cover cropping is the practice of cultivating crops amidst primary crop production, which serves as a means to maintain soil cover, rather than for yielding produce. This technique is geared towards enhancing soil health and fertility. It effectively helps in minimising soil erosion and preserving soil nutrients (Güven et al., 2023). Finally, crop rotation enhanced by appropriate farm management software can also lead to soil health improvement, reduced need for chemical inputs, and consequently sustainable land use (Lieder & Schröter-Schlaack, 2021). Thus, carbon and energy-smart practices enabled by smart farming technologies can retain soil carbon, reduce GHG emissions, enhance soil health, prevent soil erosion, and promote soil biodiversity. Economically, carbon and energy-smart practices can lead to cost savings by reducing the need for chemical inputs and fossil fuel-based energy sources and increasing efficiency. In relation to the social aspect, carbon and energy-smart practices integrated with smart farming technologies contribute to sustainable food production and the well-being of farming communities (Güven et al., 2023).

Knowledge-Smart Activities

Knowledge-smart activities, such as capacity enhancement, are integral to the adoption of smart farming technologies (Kangogo et al., 2021). These activities can be enhanced using modern technologies such as Augmented Reality/Virtual Reality (AR/VR). AR and VR can help farmers better understand smart farming technologies and practices through immersive digital environments. For example, farmers have the ability to virtually operate smart farming technologies such as robots and Internet of Things (IoT) devices and thus understand their benefits and constraints during an actual farming operation (Anastasiou et al., 2023a). Thus, the farmers are equipped with the necessary knowledge and skills to implement sustainable and climate-resilient agricultural practices without needing to purchase expensive farm equipment before understanding the potential benefits, challenges, and constraints for their farm business. As a result, these activities lead to increased productivity, cost efficiency, and overall economic gains, promote the welfare of farming communities and sustainable rural development, and ultimately, contribute to the food security and resilience of agricultural systems (Makate, 2020; Ogunyiola et al., 2022).

6.3 Barriers and Drivers for the Adoption of Climate-Smart Agriculture Practices and Technologies

Farmer adoption of digital agriculture is key to the transition towards a productive, sustainable, and resilient agriculture. Over the past decades, researchers have increasingly examined farmers' decision-making factors that affect adoption of smart farming technologies (Dessart et al., 2019; Tey & Brindal, 2012; Willy & Holm-Müller, 2013). It is now widely acknowledged that farmer decision-making is a complex and multi-faceted process that is influenced by personal, technological, organisational, institutional, and political factors (Verburg et al., 2022). When examining farmer transition to digital agriculture, it is important to adopt a food system perspective where farmers are not seen in isolation but as embedded actors in the food systems in which they operate which pose power dynamics and trade-offs that affect their behaviour (Hoek et al., 2021). To examine the multiplicity of farmer decision-making factors associated with smart farming technologies adoption and implementation, we adopt a wider perspective and categorise them into socio-demographics, psychological, farm characteristics, technology-related, systemic, and policy factors (Hoek et al., 2021).

Socio-demographic Factors

Socio-demographic factors include farmer demographics (e.g., age, gender, education, farming experience) and household characteristics (e.g., size, income). The global farmer profile is characterised by older age and low education that pose strong barriers to the adoption of smart farming technologies (Bai et al., 2022; Vecchio et al., 2020). Reports indicate that farmer age continues to increase; it is currently 58 years old on average in Europe and USA, 60 in Africa and 77 in Japan (Saiz-Rubio & Rovira-Más, 2020). Farming experience seems to partially reverse the ageing effect since as experience accrues with age, farmers are better equipped to implement digital technologies (Tey & Brindal, 2012). However, the ageing crisis calls for generational renewal and the need to attract younger and more educated farmers who are more open to innovations and less risk averse. Farmers' income (both on-farm and off-farm) plays an important role since it provides farmers with the financial resources to invest in new technological equipment (which is sometimes costly and risky) as well as with better access to credit and information sources (Begho et al., 2022).

Psychological Factors

Psychological factors encompass farmers' cognitive, affective, and dispositional factors (Dessart et al., 2019). Among the plethora of factors that have been investigated in the academic literature, motives exert a strong influence on farmers' behavioural shift to digital agriculture. It has been demonstrated that farming operations that are driven by economic gains, increased productivity, or preservation of family traditions are less likely to result in adoption of smart farming technologies compared with farming motives associated with conservation, modernisation, moral obligation, and social embeddedness (Mazurek-Kusiak et al., 2021; Pinna, 2017). A framework that has been prominently employed to explain farmer intention to adopt sustainable practices is the Theory of Planned Behaviour (TPB) (Ajzen, 1991). According to this theory, intention is shaped by three factors, namely behavioural control, subjective norms, and attitudes. In the context of smart farming technologies, behavioural control refers to the farmers' perceived ease or difficulty to perform smart farming technologies, subjective norms refer to the perceptions about what is socially approved by significant others, and attitudes refer to the evaluative dispositions towards smart farming technologies. Therefore, TPB posits that farmers are more willing to adopt smart farming technologies when they believe they have the ability to implement them, their behaviour is perceived as socially acceptable, and they hold positive attitudes towards these technologies. Similarly, farmers' awareness and knowledge about climate change and the benefits associated with smart farming technologies drive sustainable behaviour (Balogh et al., 2020). With respect to dispositional factors, the most influential are environmental consciousness and risk aversion. Farmers differ in how conscious they are about the impact of their farming activities on the environment and on their propensity to take risks, with farmers who are less environmentally conscious and more risk averse less likely to shift to digital technologies (Karali et al., 2014).

Farm Characteristics

Of the farm characteristics examined in the literature, there is general agreement that farm size is a key driver of smart farming technologies adoption. Larger farms benefit from economies of scale, reduced costs, and higher investment returns compared to small and medium sized farms (Michels et al., 2020). Furthermore, farm ownership has been linked with increased adoption rates of smart farming technologies. This is because compared to owners, farm tenants are faced with more risks, reduced financial capacity while oftentimes their decisions are constrained by the farm owner's will (Karali et al., 2014). Not surprisingly the availability of a successor affects farmers' decisions. Previous studies indicate that farmers are more willing to implement smart farming technologies that will boost profitability and environmental status of the farm when there is a successor because they seek to make their business attractive to the future owner (Barnes et al., 2019).

Technology-related Factors

Technologies are usually costly to acquire but costs can be also associated with time, effort, and training requirements by the new technologies which render the investment risky for the farmers. Hence, costs are posited to be a major barrier to adoption of smart farming technologies (Pinna, 2017). A model that has been consistently used in past research to understand farmer technology adoption is the Technology Acceptance Model (TAM) (Davis et al., 1989). According to TAM, decisions to adopt are based on the perceived usefulness and ease of use of smart farming technologies as well as perceived compatibility (added subsequently). A number of technologies are still considered complex and difficult to use which, in turn, negatively affect technology's usefulness for farming operations (e.g., farm productivity, reduced workload) and compatibility with current farming practices, goals, and values (Michels et al., 2020). Furthermore, the advent of data-driven technologies (e.g., precision agriculture), which require large amounts of data collected from farms, has given rise to data privacy and ownership concerns. Due to lack of control and transparency in the way data is collected and shared, farmers appear unwilling to share their data with technology providers and hence, to adopt these technologies (Kaur et al., 2022).

Systemic Factors

Systemic factors refer to the structures and institutions operating at the food systems level. The literature has only recently acknowledged that for food systems to shift to digital agriculture, changes are required in the decision-making of individuals in the whole value chain (Hoek et al., 2021). The social environment plays a major role in farmer adoption of smart farming technologies. It dictates whether a behaviour is approved or disapproved by a community. Social influence can be manifested through social norms, peer pressure (e.g., family, friends, and other farmers), social networks, and social learning effects. Farming communities that are more innovative and technologically advanced exert a "neighbourhood" social influence making farmers mimic their behaviour (Balogh et al., 2020). Similarly, social learning, through peer-to-peer observation of how other farmers implement smart farming technologies, drive adoption (Blasch et al., 2021). Nowadays, farmers need to possess an array of skills to remain competitive, such as entrepreneurial, marketing, and communication skills. However, there is a lack of skilled farmers and as technologies become more complex, the gap between technology advancement and farmer skills is likely to widen in the future. It is widely agreed that access to extension and advisory services such as training courses, field visits, and demonstrations, as well as technical support is crucial for farmers. Proper training and advice are linked with farmer upskilling and increased adoption of smart farming technologies (Blasch et al., 2021). A novel approach to facilitate transition to smart farming technologies is the use of collective and participatory approaches. In this sense, the collaboration and frequent interaction between farmers and other food actors (e.g., processors, retailers, and consumers) is expected to facilitate farmers' access to resources, knowledge sharing, and co-creation of pathways to change. The building of social capital will foster collective action ultimately resulting in transition of entire food systems to smart farming technologies (Pinna, 2017; Willy & Holm-Müller, 2013).

Policy Factors

Policies set the regulatory framework in which the food actors operate by specifying policy targets towards sustainability. Overall, policies are viewed in a positive light because they provide farmers with the financial means and incentives to support the transition to smart farming technologies. However, not all policy instruments are equally effective. In a European context, a comparative analysis of CAP instruments indicated that measures such as direct payments were less successful in triggering change compared to greening measures, extension and advisory services, and better access to information sources (Linares Quero et al., 2022). Moreover, a number of farmers identify inadequate compensations, bureaucratic procedures, and heavy penalties for mistakes as burdens in policy implementation (Chatzimichael et al., 2014; Pinna, 2017).

6.4 International and European Regulatory Framework

The transition to digital agriculture is considered critical by current international and European policymakers. International agreements and support from agencies such as FAO, OECD, and the World Bank along with European policies, such as the CAP and the European Green Deal, aim to promote the sustainable development of national digital agricultural systems for a sustainable, fair, and competitive future.

International Perspective

At an international level, three key organisations, namely the FAO, OECD and the World Bank, set the international vision for future food systems by influencing the design, implementation, and funding of digital agricultural transformation. Two major international agreements influence agricultural and food policies, strategies, and actions from the global to local level. The first is the 2030 Agenda for Sustainable Development, and its Sustainable Development Goals (SDGs), adopted in September 2015 (United Nations, 2015). Among the 17 goals and 169 targets, SDG 1 (No poverty), SDG 2 (Zero hunger), and SDG 9 (Industry, innovation, and infrastructure) represent the building blocks of agricultural policy and establish digital technologies as enablers of sustainable development. The second is the Paris Agreement reached in December 2015. It set out sustainability challenges, especially about meeting climate and biodiversity targets and raised the importance of fully realising the development and transfer of technology to improve resilience to climate change and to reduce GHG emissions (United Nations, 2015).

In 2016, OECD Agriculture Ministers issued a Declaration on Better Policies to Achieve a Productive, Sustainable, and Resilient global food system, which placed a high priority on digitalisation (OECD, 2016). The document outlined a set of shared goals and policy principles to ensure an integrated approach to agriculture and food policies emphasising international cooperation, particularly in trade, investment, innovation, and climate change (OECD, 2016). In the same year, the FAO and the International Telecommunication Union (ITU), together with support from partners, developed the e-Agriculture Strategy Guide aiming to assist countries in developing their national digital agriculture strategy by identifying services and solutions based on the use of agricultural digital technologies (FAO, 2016). The FAO further piloted a regional eAgri Index to assess the preparedness of European and Central Asian countries in formulating and implementing a digital transformation strategy and to provide guidance for the areas of emphasis for strategising (e.g., infrastructure, business environment, etc.) (FAO, 2018). The digital divide between small and large farms, and between developed and developing countries remains a key concern for international organisations and mainly lies in differences in skills, access to information and market environment. For instance, the OECD notes differences in the capacity of countries to generate digital knowledge by evaluating the share of expenditure for research and development in the total value of agricultural output. The USA, the Netherlands, and South Korea, for example, achieved 2.7% compared to 0.5% for Canada and Switzerland (Revenko & Revenko, 2019). To reduce the digital divide and ensure easy access to market data and information, the FAO embarked on creating open information platforms to disseminate information in the food and agriculture sectors such as the monitoring of prices, supply, and demand for food products (Revenko & Revenko, 2019).

More recently, in 2021, the World Bank developed a Roadmap for Building the Digital Future of Food and Agriculture for countries to scale up their digital agriculture (Schroeder et al., 2021). Here, the importance of innovation ecosystems, value chain actors, competition in markets, and research and development are recognised as critical for the digital transformation of food systems. The report also stresses the key role of governments in enabling access to agricultural data by providing access to open data and data-sharing platforms, setting data interoperability standards, and promoting FAIR (Findable, Accessible, Interoperable, and Reusable) principles for data use (Schroeder et al., 2021).

Finally, the OECD reports the importance of using digital technologies in agricultural policy because they improve the efficiency and accuracy of decision-making and support data-driven strategies and policies. Digital technologies enable better data-driven monitoring and compliance mechanisms, the enablement of targeted policies, and the better evaluation of the environmental impact of agriculture (OECD, 2019).

European Perspective

The EU is committed to become a forerunner in achieving the SDGs. Consequently, in September 2021, the European Commission (EC) proposed a Path to the Digital Decade (European Commission, 2021). The policy programme, guided by the 2030 Digital Compass, sets concrete targets and objectives for 2030 as a roadmap to Europe's digital transformation. The roadmap is focused on four pillars—digital skills, secure and performant digital infrastructure, digital transformation of businesses and the digitalisation of public services and proposes a set of cooperation mechanisms (European Commission, 2021). Before the Digital Decade Policy Programme (DDPP), the Digital Single Market strategy paved the way for bridging the digital divide between urban and rural areas and across EU member states, and for providing high-speed connectivity across the EU. This initiative offered many opportunities for agriculture and the food value chain to become smarter, more efficient, and more connected and was later expanded by the Strategy for Connectivity for a European Gigabit Society (European Commission, 2015). Additionally, the EU Cohesion Policy makes a key contribution to delivering Digital Single Market objectives on the ground, through significant financial allocations from the European Regional Development Fund (ERDF), aiming to overcome the digital divide both socially and geographically. To monitor progress towards the 2030 targets, the Digital Economy and Society Index (DESI) was established to evaluate Europe's digital performance based on a set of indicators capturing the four pillars of the DDPP. The 2022 report showed that, although EU member states are making progress towards digital transformation, insufficient digital skills, lack of connectivity infrastructure and investments along with low adoption of key digital technologies, such as AI and Big Data hamper growth (European Commission, 2022).

The European Green Deal comprises a set of policies that provide a roadmap to the green transition and the realisation of the SDGs following a just and inclusive transition of the food systems. In its Farm-to-Fork strategy, the flagship initiative of the legislative framework for sustainable food systems, it demonstrates the commitment to digital innovation, knowledge, and skills development in the agricultural sector. Moreover, the CAP, the main EU agricultural policy, currently accounting for 40% of the EU budget, operates a complex system of subsidies and support measures for the agricultural sector. A key objective for the period 2023–27 is for member states to form their national CAP strategic plans to modernise agriculture and rural areas through fostering and sharing knowledge, innovation, and digitalisation (European Commission, 2023b). The present CAP tools and interventions to favour the adoption of digitalisation are:

- Direct payments and eco-schemes to provide financial support for the adoption of sustainable practices;
- Sectoral interventions (e.g., fruit and vegetables, etc.) to invest in digital technologies at any stage of the supply chain;
- Investments in rural development, for instance for broadband connectivity or the installation of digital technologies;
- Farm advisory services on digital transformation of agriculture and rural areas;
- Knowledge exchange, dissemination of information, and training to boost digital skills, with strengthening the role of Agricultural Knowledge and Innovation Systems (AKIS).

At the regional level, Smart Specialisation Strategies aim to strengthen digitalisation. They focus on identifying the regions' competitive assets and strategic areas for investment, and foster innovation partnerships through better collaboration between different societal stakeholders. The 2023 European Council's report, *Conclusions on a Long-Term Vision for Rural Areas* (LTVRA), highlights that rural areas are essential contributors to EU prosperity and economic strength and to the green and digital transitions, assuming a pivotal role in matters such as food production (European Council, 2023). Digital technologies can contribute to the development of rural areas by providing better accessibility and connections (European Council, 2023). Additionally, the 2020 Industrial Strategy announced actions to support the green and digital transitions of EU industry. These actions include: (1) provide a coherent regulatory framework to achieve the objectives of Europe's Digital Decade; (2) provide SMEs with Sustainability Advisors and support data-driven business models to make the most out of the green and digital transitions; and (3) invest in the upskilling and reskilling of workforce to support the twin transitions (European Commission, 2020). The EU provides various other sources of funding that can be tapped to promote digitisation of agricultural sector, such as the Horizon Europe research and innovation programme and the agricultural European Innovation Partnership programme (EIP-AGRI).

Issues of data sharing and open access data have raised data privacy and ownership concerns. The lack of agricultural data is viewed as an impediment in the design of informed policies, better decision-making as well as monitoring and control procedures. The Declaration, *A Smart and Sustainable Digital Future for European Agriculture and Rural Areas,* noted the importance of using the European space programmes, EGNOS and Galileo, and the Earth observation programme, Copernicus, for more accurate and efficient agricultural operations (Kondratieva, 2021). Moreover, the Directorate-General for Agriculture and Rural Development (DG AGRI) collaborates with the Directorate-General for Communications Networks, Content, and Technology (DG CONNECT) to develop a common European agricultural data space to provide for the digital transformation of Europe's farming industry. Current actions are co-funded through Horizon Europe. Finally, the European Data Strategy aims to set the framework for data governance by facilitating data access and sharing for farmers and value chain actors, creating data interoperability standards, and setting standards that address any risks associated with data use (European Commission, 2023a).

6.5 Conclusion

In conclusion, agricultural sector and food systems can benefit from digital transformation and the transition to smart farming. The latter includes an array of technologies ranging from precision farming, to water-smart, weather-smart, carbon and energy-smart as well as knowledge-smart practices. These technologies have been associated with positive environmental, social, and economic outcomes. Despite the technologies being there for some time, evidence suggests that adoption remains slow and is hampered by various socio-demographic, psychological, farm and technology-related, systemic and policy factors. The policy landscape at the international and EU level is active in setting the standards, framework and regulations for the transition to digital agriculture. International organisations, such as the FAO, OECD and the World Bank influence policy-making while the EU has set a number of policies and initiatives to enable transformation. However, monitoring, control, and evaluation mechanisms are currently lacking, and hence, it is difficult to measure the effectiveness of these policies.

Future research is needed to explore the benefits and costs associated with various smart farming technologies. In particular, while the environmental and economic benefits and costs have been extensively studied in the past, evidence about the social impacts is stil nascent Understanding all three aspects of impacts will enable us to evaluate the overall sustainability of the various smart farming technologies by accounting for the trade-offs that may exist between environmental, social, and economic impacts. Moreover, more evidence on the role of systemic factors in farmer decision-making is required. A food system approach to the digital transformation of the agricultural sector acknowledges the significance of other actors, systems, and structures on farmers' decisions to adopt smart farming technologies. Gathering more insights on how the factors affect behavioural shifts and how future strategies can capitalise on their effect will be valuable. On the policy side, studies need to investigate the impact of various policies on the transition using quantitative or qualitative methodologies. Currently, several policies are in place but their performance in achieving their targets is unknown. Therefore, evaluation studies will enable measurement of their performance and adjustment or tailoring of policies where needed.

By providing incentives and removing barriers to adoption, governments can create a conducive environment for farmers to adopt smart agricultural technologies. Future policies need to take advantage of the availability of agricultural data to inform better decision-making, policy design, and monitoring. Policymakers need to create environments that enable access to data and data sharing by addressing issues concerning data privacy, ownership, and data interoperability. This will facilitate a performance-based policy design and implementation by allowing measurement of progress towards policy targets, enable the design of targeted policies while reducing the information asymmetries and power imbalances in the food systems. Based on the analysis above it is evident that future policies need to be behaviourally-informed rather than focusing on the rational-agent model. For instance, farmer differences that arise from different ages, incomes, farm sizes, economic *vs* environmental objectives, access to markets and credit, social influences should be taken into account and be differentially addressed by policies in order to remove barriers to adoption. When designing policies to foster the adoption of smart farming technologies, local entities and governments should engage in a proactive dialogue that engages farmers and other value chain actors, such as advisors, technology providers, processors, and retailers. Participatory and collective decision-making has been shown to effectively result in digital transformation of the agricultural sector. Finally, to increase policy coherence, there is a need for a systematic and inclusive assessment of current policies. Hence, policies need to establish certain monitoring and control mechanisms with specific set of indicators that will evaluate performance and enable to measure progress towards the targets and ultimately to the SDGs.

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