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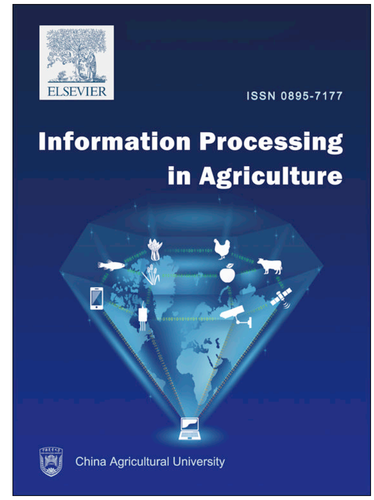

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Transition towards sustainability in agriculture and food systems: role of information and communication technologies

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Abstract

Food sustainability transitions refer to transformation processes necessary to move towards sustainable food systems. Digitization is one of the most important ongoing transformation processes in global agriculture and food chains. The review paper explores the contribution of information and communication technologies (ICTs) to transition towards sustainability along the food chain (production, processing, distribution, consumption). A particular attention is devoted to precision agriculture as a food production model that integrates many ICTs. ICTs can contribute to agro-food sustainability transition by increasing resource productivity, reducing inefficiencies, decreasing management costs, and improving food chain coordination. The paper also explores some drawbacks of ICTs as well as the factors limiting their uptake in agriculture.

Keywords: Sustainability transitions, ICT, Agriculture digitization, Food supply chain, Food processing, Distribution, Consumption.

Introduction

Information and communication technology (ICT) is a field of work and study that "*includes technologies such as desktop and laptop computers, software, peripherals, and connections to the Internet that are intended to fulfil information processing and communications functions*" [1]. Another definition for ICT comes from UNESCO [2], which states that ICT is "*the combination of informatics technology with other, related technologies, specifically communication technology*". Thus, ICT uses the newest technologies to process and communicate information. For OECD [3], the main function of ICT is to "*capture, transmit and display data and information electronically*" (p. 5). According to the World Bank [4], "*Information and Communication Technologies consist of hardware, software, networks, and media for collection, storage, processing, transmission, and presentation of information*". They include radios, TVs, telephones, computers, Internet technologies, and databases.

Communication, information exchange, transactions, knowledge transfer are fundamental in nearly every aspect of agriculture. Therefore, digitization of agriculture and food chains is high on the political agenda. For instance, there was an entire part dedicated to ICT in agriculture in the G20 Agriculture Ministers' Action Plan 2017. In the Action Plan, the ministers renewed their commitment to advance ICT innovation to improve the efficiency and sustainability of the agricultural sector [5].

The food system is strongly related to many sustainability challenges such as climate change, biodiversity loss, water scarcity, and food insecurity [6–11]. For that, there were many calls for sustainability transitions in food systems [12–14]. Sustainability transitions can be defined as "*long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption*" [15](p. 956). In agriculture, the notion of sustainability transition applies to a shift from an agri-food system having as a main goal to increase productivity, to one built around the wider principles of sustainable agriculture [16]. According to Spaargaren et al. [17], food sustainability transitions refer to structural changes that give rise to new production and consumption modes and practices that are more sustainable.

Sustainable agri-food system is a knowledge-intensive system that requires a new kind of knowledge. Knowledge and related information, skills, technologies, and attitudes will play a key role in sustainable agriculture [18]. It is claimed that moving towards sustainability in agriculture and food systems call for innovative solutions and appropriate technologies such as ICT [19,20]. ICTs hold the potential to contribute to sustainability transitions in agriculture due to their disruptive potential [21]. According to Wolfert [22] and Poppe [23] disruptive ICT trends include mobile/cloud computing, Internet of Things, location-based monitoring (remote sensing, geo information, drones, etc.), social media and Big Data (web of data, linked open data). Sui and Rejeski [24] discussed sustainability implications of increasing use of ICTs in the context of the digital economy. Other authors highlighted ICT potential for sustainable development [25–30], human well-being [31].

The first use of ICTs in agriculture dates back to the 1960s. In 2003, the World Summit on the Information Society addressed *e-agriculture* and highlighted as a priority the application of ICT in agricultural development [32,33]. ICTs are increasingly used in modern agri-food sector [34] and they have also been put forward as a means to enhance agri-food systems sustainability and to achieve food security. Svenfelt and

Zapico [35] reviewed the potential of ICT solutions for improved sustainability of agri-food systems by increasing efficiency, enhancing transparency and traceability, creating network between food chains actors, and improving food practices. The same authors argue that the way ICT is used in the solutions to improve sustainability in the food chain can be related to the Visible-Actionable-Sustainable ideas of Bonanni et al. [36]; ICTs make the food system and its impacts 'visible', to render it 'actionable' (cf. optimization, decision-making, etc.) for making it more sustainable.

This review provides an analysis of how ICTs helped to move towards sustainability in agriculture and food systems. It analyses sustainability benefits of ICTs in agriculture/food production, processing, distribution and consumption as well as in terms of food chain integration and coordination. It also sheds light on some criticalities and drawbacks of increasing use of ICTs in agri-food systems.

ICT in food production: beyond precision agriculture

The role of ICTs in increasing system efficiency is a central theme in literature on ICT for sustainability [30,37–39]. ICTs have been also used for a long time to improve resource efficiency and productivity in food systems [21,35,40]. In fact, ICT can help decreasing the use of agricultural inputs (fertilizers, pesticides, energy and water) as well as reducing environmental externalities [34].

Many farms across the world are applying big data and data analytics to improve productivity of agricultural practices. These so-called 'AgInformatics' systems are being heavily invested in by multinationals such as Dow AgroSciences, Deere Co, and Monsanto. They are being applied in a broad variety of farming activities such as equipment maintenance, fields mapping and other operational activities to optimize irrigation, sowing, etc. These solutions are becoming affordable but a key factor in their development will be margins on sales of agricultural produce [21]. In fact, the key factor discouraging more widespread adoption of ICTs in agriculture is profitability i.e. demonstrating that uptake of ICTs improves farm profitability [41]. There are numerous examples of data exchange platforms in agriculture. These include Fieldscripts, Farm Business Network, Farm Mobile, Agriplace, FIspace [23]. In the developed world, ICTs serve as a basis for other technologies such as geographic information systems (GIS) and global positioning systems (GPS) in precision and site-specific agriculture [10].

A widely cited example of the use of ICT in agriculture in order to increase efficiency is that of precision agriculture [42–45]. Precision agriculture is a modern farming model that consists in the utilization of sensors to optimize the use of pesticides, fertilizers and water [41]. It came into use in the 1980s as GPS became accessible by some farmers especially in developed countries, such as in the European Union (Box 1). Modern precision farming makes use of GPS as well as sensors, GIS technology and advanced software. The methods of precision farming rely mainly upon a combination of satellite navigation and positioning technology, new sensor technologies, and the Internet of Things [46].

Precision agriculture technologies (PATs) include Variable rate nutrient application, Variable rate irrigation, Variable rate pesticide application, Variable rate planting/seeding, Precision physical weeding technology, Machine guidance (driver assistance or auto-guidance), Controlled Traffic Farming (a system confining all machinery loads to permanent traffic lanes) [43]. In variable rate technologies, data from different sensors allow tailoring input amounts to current needs of crops and differences between parts of the same field, instead of applying the same amount to the whole areas. This reduction of input use has positive environmental [43,46–51] and economic [43,48,49,52–61] impacts. ICT-based decision-support systems help farmers to maximize production efficiency while minimizing production costs and environmental footprint of their operations [49]. ICT-based smart irrigation systems can reduce not only water usage [50,62,63] but also carbon footprint [50] due to reduced use of energy. In general, precision agriculture technologies and practices can result in lower GHG emissions, thus mitigating climate change, due to enhanced of carbon sequestration ability of soils [64] thanks to reduced tillage [65] and nitrogen rates [66,67]; reduced fuel consumption in field operations [43]; and reduced inputs use [60].

Box 1. Precision farming in the European Union.

Precision farming is presented as a means to foster a new 21st century agricultural revolution in the European Union (EU). In fact, it is expected that a wide adoption of precision farming techniques will allow the EU to ensure agro-food sector sustainability whilst increasing agricultural output. The adoption of precision farming has the potential to contribute to meeting increasing food demand whilst ensuring food production sustainability by promoting a more resource efficient approach to agriculture (crop production, animal husbandry), forestry and fisheries. ICTs hold the potential to effectively reduce production costs and substantially increase yields, thus boosting local economies in rural areas. In addition to these economic benefits, precision farming also promises multifaceted environmental benefits by reducing the use of agro-chemicals, such as fertilizers and pesticides, as well as decreasing contribution of agricultural sector to greenhouse gas emissions. Therefore, the EU has supported cutting-edge research and innovation (cf. FP7 and Horizon 2020 programs) into the use of ICT in agriculture sector and this promises developing exciting solutions. With the explosion in the digital revolution, technologies using 'the Internet of Things' or Big Data allowed the advancement of numerous precision farming techniques. It is estimated that about 70 to 80% of new farm equipment in the EU have some form of precision farming component. Technologies of precision farming are nowadays not only present in all crop production stages (soil preparation, seeding, crop management, harvesting), but are also increasingly used in animal husbandry.

Source: European Union [48].

Technologies of precision farming are nowadays present in all crop production stages and increasingly used in livestock production to improve both cost effectiveness and overall sustainability of operations [68]. Precision farming technologies are currently taking up with an expected annual growth rate of 12% till 2020. The European Union [46,48,69,70] and the USA are considered the most promising markets. In the conclusions of their foresight exercise on precision agriculture and the future of farming in Europe, Schrijver et al. [46] highlighted that precision agriculture can actively contribute to food security and supports sustainable farming (i.e. environmental sustainability of farming). There has been over last decades an increasing attention to precision agriculture also in the United States as shown by focus on these new technologies by extension services [71–75]. Nevertheless, precision agriculture technologies are still not affordable for many farmers in developing countries.

There has been in recent years an increasing interest in the use of ICT for development (cf. ICT4D). It is widely believed that ICTs hold the potential of contributing to agricultural and rural development in developing countries [19,29,32,33,76–80]. The e-Sourcebook developed by the World Bank, provides guiding principles and examples on applying ICT in agriculture in poor rural areas [81]. Also the relation between ICTs and food security was the object of many publications [19,32,33,82]. Arguing that the failure of the original green revolution in Africa was also due to poor access to ICTs [83], infoDev [84] assumes that a real hope for a different outcome is offered by the current mobile revolution in the continent. In fact, there is a tremendous increase in the use of mobile phones also in African countries [85]. ICTs can improve rural livelihoods and empower small-scale farmers in developing countries by enhancing their connectivity [78,80] and increasing availability of agricultural and market information [84]. ICTs can also contribute to social justice and equity by empowering marginalized groups (e.g. women, the elderly, youth) in rural communities of the Global South [77]. ICTs empower farmers as innovators by accruing their access to information leading to innovation [86,87]. Agricultural innovation is about timely access and application of available information to respond to opportunities and threats [88]. In developing countries, ICTs are widely used by extension and advisory services to provide farmers with information and advices (e.g. weather forecasts, crop and livestock diseases, market information prices), through Short Message Service (SMS), web portals and call centers [79,89,90]. While before SMS dominated, there is nowadays a more varied mix of technological options such as SMS, smartphone apps, IVR (Interactive Voice Response) as well as integration with social media [32,91,92]. Thanks to ICTs, some innovative extension models and services – such as the Virtual Extension, Research and Communication Network (VERCON) of FAO – were developed [79]. ICTs, especially mobile telephony, allow farmers, also in developing countries, to access financial services (e.g. savings, credit, insurance, payment facilities and money transfers) that they need at low cost [32,81].

ICT in food processing, distribution and consumption

While ICT innovation was mainly used in the last decades to improve agriculture productivity and efficiency, and they continue to be so, there is also a growing interest in ICT solutions for post-harvest, transport and storage stages of the agricultural value chain [32,40].

ICTs can benefit transport systems at various levels in terms of cost reductions and efficiency increases [93]. In some situations, they can also help to overcome some problems in transport infrastructure. The cost of food transportation, and eventually also that of food processing, can be reduced if the limited transportation facilities are used more efficiently [33]. ICTs and sensor-based applications can be used to enable evaluation of the current situation in transport logistics; they can be used to optimize transportation and logistics processes by monitoring different parameters such as fuel usage, speed and position thus making the supply chain more efficient [34]. Some applications, such as Sourcemap, allow visualizing supply chain information in relation to environmental impact (cf. carbon footprint, food miles). Sourcemap has been effectively used for improving the efficiency and sustainability of ingredient sourcing, by reducing distance between ingredient production sites and processing plants thus reducing transportation costs [36].

ICT is used for facilitating retailing ways. E-commerce, online ordering and deliveries, can potentially substitute traditional retail [94] and allow a better coordination of food distribution. While most scholars agree that transportation costs can be reduced with use of ICT purchasing systems [95], there are divergences with regard to the effect on environmental impact of distribution. Siikavirta et al. [96] showed that e-grocery home delivery could reduce greenhouse gas emissions (GHG) in Finland. Williams and Tagami [97] found that in dense urban areas, traditional retail had lower environmental impact than e-commerce. In fact, it seems that the environmental impact of e-commerce depends on the efficiency of transportation. Therefore, business-to-consumer and business-to-business transportation need to be efficient if e-shopping is to improve environmental sustainability [24]. According to Börjesson Rivera et al. [94], food ecommerce, particularly e-retailing, can improve food chain sustainability by enhancing transparency and knowledge sharing.

The use of ICT to change every day behaviour and practices towards sustainability is a main research topic in ICT for sustainability (ICT4S). Nevertheless, much of research related to this area has focused on energy; although, as in the case of sustainability transitions research field, the area of sustainable food is receiving an increasing interest [98–100] with the aim of closing the intention-behaviour gap that explains differences between current food consumption practices and sustainable food consumption patterns [101], including sustainable diets. These include applications that visualize food carbon footprint to consumers [102] and food-miles [103].

ICT and food chain: it's not a panacea!

ICTs are impacting the organization, integration and coordination of food chains at local, regional and global levels. They are reported to reduce transaction costs in the food chain. According to Berti and Mulligan [21] "*digital technologies may hold the key to the successful coordination of a more sustainable food system*" (p. 7). They are useful for both industrialized food supply chains and short ones. Different types of farms (industrialized farms, multi-functional farms, urban farms) require different types of ICT-enabled coordination mechanisms. Rural farms need to coordinate their logistics and take-to-market activities as well as to understand where and when to obtain the best market price. Peri-urban farms need coordination to deliver their products to the correct market and customers. Urban farms need direct coordination with consumers or other small urban producers.

Modern ICTs are improving access of farmers to information thus giving them multiple options for buying inputs and selling outputs [80,104,105]. This increased bargaining power of farmers (including small-scale ones) represents a clear revolution in the food chain and has far-reaching implications in terms of transitions towards sustainability in food systems. It implies also new relations between producers and consumers that are based on more equity and transparency. Moreover, ICTs, such as mobile phones, shorten the distance between food chain actors involved in producing, processing, transporting and marketing food [83].

Verdouw et al. [106] argue that food system sustainability can be dramatically enhanced through the revolutionary potential of the Internet of Things (IoT) perspective that can allow visualizing, monitoring, controlling and, thus, optimizing food chain processes by self-adaptive, autonomous and smart ICT systems. Furthermore, internet technologies and ICTs contributed to the development of new agri-food chain concepts (e.g. food webs, urban agriculture) in which regional producers and consumers are connected

[22]. In fact, ICTs have played an important role in improving communication and coordination between the different parts of short supply chains, especially producers and consumers [21].

Some scholars [107–110] argue that ICTs have the capability of increasing the transparency of supply chains. ICT and information systems can be used to increase the traceability of agro-food products and the transparency of the food chains. They make easier, in fact, information management and increase information integrity [111]. Traceability systems have become important to guarantee food quality and safety. Current traceability systems are mainly used to find the origin of problems and facilitating call-backs [108].

ICTs have contributed to the emergence of many alternative food networks (e.g. farmers' markets, community-supported agriculture) and short supply chains [21]. The internet is being used, among others, for creating knowledge networks between producers and for re-connecting farmers with consumers. This connecting of different food system actors can provide opportunities for increasing sustainability [27,112]. Although the main feature of farmers' markets is face-to-face contact, ICT can be used to establish and empower trust relationships between producers and consumers in farmers' market [113]. However, Murphy [114] argues that e-commerce hides the real work in the food chain to consumers and this could enlarge the distance between producers and consumers. The internet has been also increasingly embraced by community-supported agriculture (CSA) operations as a way to organize the distribution and planning of their produce [35]. In fact, some CSA operations offer basket schemes that imply home deliveries of fresh produce, mainly vegetables and fruit.

ICTs have been used successfully in many countries and regions for connecting small-scale farmers (e.g. communities of practice, networks) [21,115]. They allow creating interaction space to share knowledge and expertise among the members of communities of practice [116]. Communities of practice range from local to global. For instance, the *e-Agriculture* community (http://www.e-agriculture.org) is a global community of practice - launched by FAO and other organizations in 2006, after the World Summit on the Information Society (WSIS) held in 2003 and 2005 – that allows exchange of ideas, information, and resources on the use of ICT for improving rural livelihoods, empowering rural communities, and creating enabling conditions for developing sustainable agriculture and achieving food security [32].

ICT has been crucial also for the development of urban gardening, which is another alternative food production method that connects producers and consumers. For instance, different internet services provide access to land by urban gardeners by connecting them with landowners that are interested in sharing part of their land. Furthermore, some ICT applications allowed creating peer food networks that provide solutions for dealing with produce surpluses to avoid food waste, which represents a waste of resources such as freshwater, cropland and inputs (e.g. fertilizers) [117]. This is the case of food banks that developed in many countries [118].

Despite their well-documented positive implications in terms of food chain sustainability, the use of ICT can also bring about some negative impacts (Table 1). Davies [99] pointed out that ICT solutions that are developed in isolation from realities and practices of producers and consumers run the risk of hampering rather than advancing possibilities for sustainability transitions in the food system. Svenfelt and Zapico [35] highlighted the need to adopt a holistic approach that takes into consideration links in the food chain; otherwise, sustainability gains in one part of the food chain may induces offsetting changes in another part. Therefore, ICT solutions should consider production practices, communication in food chain, consumer behaviour [35]. The ownership of data is a key concern with the use of digital technologies in the food chain both on the supply-side (cf. producers) and the demand side (cf. consumers) [21]. For instance, large companies are able, thanks to feedback loops on equipment they sell, to collect a large amount of data about farms and this represents a big concern for farmers. Agro-chemical multinationals that possess data on a large number of farms in different countries may use them to create a monopoly on market of staple crops with implications in terms of food security and farmers' livelihoods in developing countries.

Table 1. Impacts of ICT use on agro-food chain sustainability.

Sustainability dimension	Expected positive impacts	Potential negative impacts
Environmental	Increasing efficiency of the use of resources (water, land, energy) and inputs (fertilizers, pesticides) Reducing footprint and negative environmental externalities of agriculture and agro-food processing (e.g. water pollution) Decreasing contribution of agricultural sector to greenhouse gas emissions Reducing of food losses and waste	Generating e-waste and disposal of ICT equipment in rural areas
Economic	Reducing production, transport and distribution costs Increasing productivity and profitability Reducing transaction costs in the food chain Connecting small-scale producers to	Initial increase of production costs because of investment Increasing risk of agro-food market dominance by few multinationals

	markets	
Social	Increasing transparency of food supply chains Making easier access to information by all food chain actors Improving product traceability / food safety (cf. consumer health) Fostering networking among food chains actors Empowering small-scale farmers by enhancing their connectivity Improving food practices	Disconnecting producers and consumers through virtual relations Increasing dependency on technology Increasing the power of globalisation Risk of increasing exclusion of small-scale and computer illiterate producers

Challenges to ICT use in the food chain

There are many challenges that should be addressed in order to increase the use of ICTs in agriculture and food system [79,80]. Wolfert et al. [119] identified some bottlenecks of development of ICTs in agriculture such as small-scaled and isolated software development, regional focus and cultural differences, difficult or impossible interoperability between various systems in the supply chain or at farm level, complicated handling and integration of large amounts of data (e.g. data from agricultural equipment). Schrijver et al. [46] pointed out that the use of ICTs, especially in the context of precision agriculture, will trigger societal changes, especially in rural areas. Moreover, uptake of precision farming technologies can represent a challenge for farmers that may need to learn new skills.

In the Global South, several factors such as connectivity, content (e.g. cultural appropriateness, language), capacity, and cost can challenge the integration of ICTs in agriculture and rural economy [77]. Therefore, ICTs, such as mobile technologies, need to be tailored to individual contexts and be developed in collaboration with end-users and beneficiaries to ensure that they are adequate, relevant and accessible [77,81].

FAO [32] identified seven critical factors of success and challenges in making ICTs available and accessible for farmers and rural communities:

- Content (adaptation of content to farmers' needs in terms of format and relevance);
- Capacity development (ability to effectively use technologies and information at individual, organizational and institutional levels);
- Gender and diversity (difficult and limited access for women, older and poor farmers, and people living in remote areas);
- Access and participation (gender-based and rural-urban digital divides persist);
- Partnerships (few and mostly ineffective public-private partnerships);
- Technologies (challenge of identifying the right technologies mix that is suitable to local contexts);
- Economic, social and environmental sustainability (difficult scaling up of pilot ICT projects and initiatives).

Conclusions

Food systems need a radical transformation to become sustainable. ICTs can contribute to this food sustainability transition by providing new ways of visualizing and measuring impacts, communicating necessary changes and connecting food chain actors. New ICT technologies and services help food operators deliver greater efficiency in resource use. Therefore, digital technologies hold potential of reducing inefficiencies within food supply chains. They are also critical in helping to bring about the changes in food consumption patterns and practices needed to move towards sustainability in the food chain. In order to maximize the benefits of ICTs in food chains, also in developing countries, it is necessary to develop applications and services that are user-friendly, relevant, localized and affordable. Actions in policy, science and innovation are necessary to encourage the development of affordable, locally appropriate, and sustainable ICT infrastructure, applications, services and tools for agriculture and the rural economy.

ICTs can have both positive and negative impacts related to sustainability in agro-food systems. In fact, ICTs deployment induces far-reaching changes that impact individuals, societies and the environment. Agriculture is changing significantly with the multiplication of devices and their increased connectivity. Aside from the benefits of digital innovations, there are also challenges and threats that need to be addressed. Therefore, more research is needed on the impacts of ICT solutions and applications in terms of agriculture and food systems sustainability. Such a research should adopt a holistic approach and consider the complexity of food system as well as interaction between its different components and actors. Nevertheless, it is also important to first define how a sustainable food system should look like in each specific context, then to see how ICT can support the journey towards sustainability. In fact, there is the risk with ICT to increase the power of globalization, which can lead to uniformity of food systems worldwide.

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Conflicts of Interest

No conflict of interest is confirmed by both of authors.

Transition towards sustainability in agriculture and food systems: role of information and communication technologies

Highlights

- ICTs can contribute to transition towards sustainability in agro-food systems.
- ICTs have positive environmental, social and economic impacts on agriculture, food processing, distribution and consumption.
- Many barriers should be overcome to increase the use of ICTs in agriculture in the Global South.
- Increase of ICTs use in agro-food chain encompasses some risks that should be properly handled.