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Review

Digitalization for Sustainable Agri-Food Systems: Potential, Status, and Risks for the MENA Region

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Abstract: Digital technologies offer a potential solution to improve sustainability—economic, social, and environmental—of agri-food systems around the globe. While developed countries have led the innovation and adoption of digital agriculture, the potential impact in developing countries—including in the Middle East and North Africa (MENA) region—is massive. This article synthesizes existing evidence to review the potential and current contribution of digital technologies to the agri-food sectors in MENA. Digital agriculture shows promise in addressing the key challenges facing the agri-food sector across MENA countries. Improvements in primary production, supply chain and logistics performance, and optimized use of scarce natural resources (notably agricultural water) could be notable, if digital technologies can be implemented as envisioned. Available evidence shows that adoption of digital agriculture is at early stages, generally led by high-value agricultural production targeting domestic markets in Gulf countries and export markets in Mashreq countries. Economic sustainability appears the strongest force for current adoption, with less focus on social or environmental sustainability. Public policies should not only foster the adoption of digital technologies in MENA but also ensure equity of access, transparency of use, data protections, and labor protections. Policymakers should move beyond traditional, production-centric views to deliver also on social and environmental sustainability.

Keywords: productivity; efficiency; sustainability; food security; agriculture; digital agriculture; smart farming; digitalization; digital technologies; Middle East and North Africa

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1. Introduction

The term "digitalization" refers to the socio-technical application of digital technologies or innovations [1]. Digital agriculture (sometimes also termed "smart farming") refers to the design, development, and use of digital technologies in agriculture and the wider agri-food sector. Digital agriculture encompasses a range of technologies that include sensors, robots, digital communication tools, blockchain, computational decision and analytical tools, and cloud-based technologies [2]. Controlled-environment agriculture (greenhouses, indoor farms, and vertical and hydroponic farms) increasingly applies digital technologies including sensors, robots, and digital communication. More advanced approaches leverage digital, mobile, internet of things (IOT), and cognitive technologies. For example, precision agriculture relies on tools including global positioning system (GPS)-enabled guidance, control systems, sensors, robotics, drones, autonomous vehicles, and variable rate technologies. Precision agriculture practices for livestock farming include sensors, radio frequency identification (RFID), and automated or robotic milking and feeding systems. Predictive analytics software and/or artificial intelligence (AI) use available data to provide farmers with guidance about crop rotation, optimal planting times, harvesting times, and soil management.

Digital technologies have been touted as a potentially revolutionary solution to improve agricultural production systems' performance and sustainability [3], defined to have economic, social, and environmental dimensions [4,5]. Digital technologies can make the agri-food sector more efficient, inclusive, and environmentally sustainable, thereby increasing benefits for farmers, consumers, and society at large [6]. Digital technologies can help to raise on-farm productivity, improve resource use efficiency, and support climate resilience [7]. Improvements in primary production, supply chain and logistics performance, and reductions in food losses and waste are especially notable, provided that digital technologies can be implemented. Moreover, the COVID-19 pandemic has increased attention to both the need for and utility of digital technologies including within the agri-food sector [8] and has catalyzed the introduction and adoption of digital technologies [9]. Despite the myriad benefits promised, digital agriculture—like other, major innovation breakthroughs—is not without its challenges or risks [6,10].

While developed countries have led much of the innovation and early adoption of digital technologies [11–14], the potential impact of these technologies on agriculture in developing countries is massive given the economic, social, and environmental roles played by their agricultural sectors [6]. The available literature has tended to focus on developing countries and regions that depend most highly on agricultural production, where agricultural production is viewed as a key economic sector or where the agri-food sector is a major employer.

The Middle East and North Africa (MENA) region has received little, albeit growing, attention within the field of digital agriculture [14] and vice versa [15]. This tendency to overlook the MENA region is despite the fact that agriculture continues to be practiced and that agri-food is an important, if relatively small, sector within most countries of the region and may reflect the fact that the sector is severely constrained by both natural and human factors [16], which may limit expectations for agriculture in MENA. Nevertheless, the sustainable development of the agri-food sector remains of critical importance for economic performance, employment, social stability, and food security.

The research questions motivating this article are as follows: (1) What are the challenges to the sustainability of agriculture in the MENA region? (2) To what extent can digital agriculture address the actual challenges facing the sector, across all three pillars of sustainability? (3) What is the current status of digital agriculture in the MENA region? (4) What policy action is needed to unlock the potential of digital agriculture and truly contribute to sustainability in the MENA region? Accordingly, this review article seeks to synthesize existing evidence to provide a tightly focused overview of the potential and current contribution of digital technologies to the agri-food sectors of MENA countries. This article does not offer new empirical evidence but rather synthesizes available knowledge to lay the groundwork for such future contributions to the literature. The article is structured as follows: Section 2 briefly describes the materials and methods used. Section 3 presents the results of the literature review, including a summary of the status, contributions, and challenges of agri-food in MENA countries; the potential contribution of digital technologies to the sector; and the current status of digital technologies within the MENA region. Section 4 presents the discussion and conclusions. Evidence shows that adoption of digital technologies within the agri-food sectors across the MENA region varies but is generally at early stages and led by high-value and export-oriented agricultural production. Policies are needed not only to foster the adoption of digital technologies in MENA but also to address concerns for equity of access, transparency of use, data protections, and protections against adverse labor impacts.

2. Materials and Methods

This research consists of a scoping review of the literature addressing the potential and current contribution of digital technologies to the agri-food sectors of MENA countries. The review draws on both academic and grey literature, including publications from institutions such as the World Bank and the Food and Agriculture Organization of the United Nations that play a significant role in policies and interventions targeting the application of digital technologies within the agricultural sector in developing countries [3,17]. News articles have also informed this review, to address the most recent developments not yet reflected in the academic press. Publications were identified through searches of academic databases (Web of Science) and open internet sources (Google search), and through the "snowball" referral to bibliographic references identified in relevant publications. Given the rapid evolution of digital technologies, this review has prioritized more recent studies (published since 2000), though has not strictly excluded earlier publications of relevance to the topic.

A systematic approach to the literature review was neither practical nor appropriate: A search for peer-reviewed academic articles addressing "digital agriculture" or "smart farming" within the MENA region or any of the corresponding countries (pairwise combinations, both within the TOPIC field in Web of Science) yielded precisely one result (Table S1). Moreover, the objectives of this research are to provide a synthesis of the evidence on the potential of technology application and its current status in MENA and to extrapolate lessons for policy relevance, rather than to provide an exhaustive examination of any single digital technology.

This research delimited the MENA region to include the 22 member countries of the Arab League. Given the nature of this review, the de facto focus is accordingly on those countries for which more evidence is available.

3. Results

3.1. Agri-Food in MENA—Sustainability Considerations

The agri-food sector makes a modest but important contribution to the economy of countries in the MENA region, particularly those countries that have already experienced the structural transformation of their economies. Nevertheless, the sustainable development of the agri-food sector can play a key role in informing economic performance and employment, social stability and inclusion, and environmental outcomes. Indeed, sustainability of agri-food systems needs to encompass the multiple pillars of sustainability: economic, social, and environmental [4,5,18].

3.1.1. Economic Contribution

The relative contribution of the agriculture sector to the total economy is a minor share in all MENA countries, ranging from less than 1% in Gulf countries like Bahrain, Qatar, and the United Arab Emirates to a high of more than 30% in Comoros (Table S2) [19]. Despite this small share, growth in agricultural production can stimulate growth in the wider economy and especially other areas of the agri-food sector, including production of inputs, food processing, logistics, and financial services. The economy-wide multiplier effect of the agricultural sector may be significant in developing countries, suggesting strong potential for investment in the agriculture sector to trigger wider economic growth [20,21]. In MENA, the downstream segments of the agri-food sector have demonstrated dynamism and faster growth in recent decades as compared to on-farm performance [22].

The agri-food sector can be an important contributor to the net trade performance of MENA countries, offsetting imports and increasing exports. Increasing agriculture's productive potential could help to reduce the dependence on food imports, which is high. For example, Iraq imports more than 80% of its food needs (including most cereals, meat, refined sugar, cooking oil, canned and processed foods, fruits and vegetables, and dairy products) [23]. Food import dependence in MENA countries is projected to rise in coming years due to population growth and shifting dietary patterns. Moreover, this dependence was illuminated during the COVID-19 pandemic, when shocks to international supply chains led to calls for shortened supply chains and sustained local agri-food production, including through digital technologies [8,24]. Improved agri-food performance can also help improve trade balances via the export channel. The expansion of agri-food exports can increase foreign currency inflows, which would be especially welcome in countries such as Lebanon where foreign currency is scarce [25].

3.1.2. Social Contribution

As a labor-intensive sector, agriculture plays an outsized role in employment and job creation in nearly every country of the MENA region. In fact, agricultural employment as a share of total employment is higher than agriculture as a share of GDP in every country in the region for which data are available, except Algeria and Jordan. Agriculture accounts for a minor share of employment in the Gulf countries and Jordan, but a relatively higher share in the other countries of the region, rising to half or more of all employment in Comoros, Mauritania, and Somalia (Table S2) [19]. The agricultural sector also has relatively strong potential for further job creation, as the long-term value-added elasticity of employment in the MENA region is higher for agriculture than the industrial or service sectors. For every percentage point of growth in the value added of the agriculture sector, employment increases by 0.36 percentage points (versus industry at 0.30 percentage points and service at 0.20 percentage points). Employment is created along the value chain, from production to processing, packaging, and distribution and with spillover effects on related sectors such as services, transport, and communications [26].

Poverty is concentrated in rural areas, where households disproportionately depend on agriculture as a primary source of income. The prevalence of poverty in rural areas is reported to be higher than in urban areas in every MENA country for which data is available (Table S2) [27]. As employer to many of the poorer and more marginalized segments of the population—such as migrants, refugees, and the internally displaced—agriculture can play a critical role in reducing poverty and vulnerability. For example, in Lebanon, the agriculture sector was the second-highest employer of displaced Syrians who were working in 2019 (17% of those who have a regular job); this figure was reported at 27% among children [28]. In Iraq, agriculture has proven critical to resettlement of internally displaced persons: 47% of people returned to rural areas, where agriculture, farming and animal husbandry ranks among the top three sources of income. Evidence showed that, as of 2019, returns were higher in locations where agriculture, livestock, and agricultural market activities had resumed [29]. Technologies that boost land and labor productivity may provide a direct path out of poverty. In terms of employment and labor demand, productivity growth in agriculture accumulates additional purchasing power among rural families, expanding job opportunities in off-farm sectors and thereby releasing labor to non-farm sectors [30]. The combination of appropriate investments and proper enforcement of social protections can allow agriculture to progress towards social inclusion and vulnerability reduction among its labor force.

The agri-food sector, as a component of the food system, has direct and indict impacts on food security [31]. Countries of the MENA region report significant food insecurity according to a range of indicators (Table S2). Undernourishment affected approximately 9.0% of the regional population as of 2017–2019, and 30.2% of the population suffered from moderate or severe food insecurity (figures are reported for the Western Asia and Northern Africa regional definition, which approximates but does not precisely correspond to the MENA region as defined within this article). Concurrently, some 27.7% of adults in the region were obese (2016 data) [32]. Support for the agri-food sector and improvements in its performance could improve the region's food security status by supporting agricultural development and incomes, as well as the production and consumption of more nutritious foods [33,34]. Insofar as food security contributes to social stability, the agri-food sector therefore also makes a contribution [35]. Moreover, food systems globally—including within the MENA region—must change fundamentally in the coming decades to align with the needs of healthy people, a healthy planet, and healthy economies, while sustainably increasing the food supply by 2050 [36].

3.1.3. Environmental Contribution

The principal environmental "contribution" of the agricultural sector in the MENA region is in fact as a major user—and polluter—of natural resources including water and land, as well as a contributor to biodiversity loss and climate change. The sector is thus both agent and victim of environmental harm [5].

The agricultural sector is the largest single user of water in multiple countries of the MENA region [37], a region which is one of the most water scarce on the planet. Most countries of the region are categorized as “extremely high” or “high” baseline water stress, and a number are ranked among the most water stressed in the world (Table S2) [38]. To manage this scarcity of water, irrigation is frequently employed for crop production; the use of modern technologies such as drip irrigation and hydroponics can multiply water productivity and produce more with less water. Though water is a scarce resource, agricultural water use efficiency remains low in many countries of the region [39]. Indeed, while water scarcity is a challenge at the national level, it may be less so for individual farmers who can access sufficient water through groundwater resources, even if these resources are threatened by over-extraction and declining quality. Widespread water pollution and substandard water infrastructure exacerbate water scarcity and complicate government efforts to manage the water demand of the agricultural sector. In agricultural areas, the runoff and infiltration of fertilizer and pesticide residues contributes to further environmental degradation. In light of water scarcity, expanding agricultural production and exports must be balanced with the sustainable use of scarce natural resources, specifically irrigation water. For example, experts have recommended against the expansion of irrigated agriculture within the Tigris–Euphrates watershed due to already excessive water use that has led to declining water tables and soil salinization [36]. The sustainable use of water resources is among the most pressing food production challenges in the Gulf [40].

Arable land is another key limitation to agriculture in MENA countries and is under threat from encroaching desertification. Desertification is estimated to affect some 75% of Iraq’s land, for example, contributing to the displacement of farming activities [41]. Declining soil fertility is a pervasive problem and expected to limit future agricultural productivity in the region.

Unsustainable use of agricultural inputs, including fertilizers, pesticides, and herbicides, is damaging the current export potential and long-term sustainability of agriculture. Excessively high levels of fertilizer use can reduce yields over the long term. Excessive and inappropriate (ill-timed) application of pesticides may reduce the quality of production, limiting exports to markets that impose strict food safety and sanitary and phyto-sanitary (SPS) standards [26].

MENA’s agri-food sector is a contributor to global climate change through its production of greenhouse gas emissions (GHGE) associated with every stage of the value chain. While the total GHGE attributed to agriculture (including agricultural land use) are not available at the regional level, these range widely from less than 1% in GCC countries where agricultural production is relatively limited and where energy production is significant (e.g., Bahrain, Kuwait, Qatar, Saudi Arabia, and United Arab Emirates), to more than 50% in Somalia and Mauritania (Table S2) [42].

3.1.4. Key Challenges

Agricultural production in the MENA region is constrained by challenges including scarcity and inefficient use of natural resources (notably water); small and fragmented farm structures; suboptimal agricultural practices and poor management due to weak extension services; poor integration of input and output markets; limited access to finance; weak infrastructure; and lagging food safety and traceability standards. These challenges disproportionately impact smallholder farmers (as compared to larger, commercial farmers), due to factors such as their lower production volumes, higher transaction costs, more limited capacity for investment, reduced market access, and weaker bargaining power [16,43].

In a number of countries of the MENA region, conflict and social unrest have challenged the performance of the agricultural sector in recent decades. Violent conflict such as that experienced in Iraq may destroy, disrupt, or deteriorate infrastructure, resources and productive assets, institutions, and value chains, e.g., [23,33,35].

Climate change exacerbates the existing challenges the agriculture sector is facing in the MENA region, undermining rural livelihoods and potentially leading to more fragility, displacement, and tensions. Climate change has and will continue to impact temperature and precipitation patterns, raising the risk of extreme weather events. The average temperature in the MENA region may increase by up to 4.8 °C by 2100, with a higher rate of warming in summer than winter. Crop yields in MENA could fall by 10–20% by 2050 under worst-case scenario models. Livestock productivity will fall due to less available animal feed, increased animal heat stress, and a higher risk of infection and disease. Climate change is expected to disproportionately affect small-scale farmers, who are more vulnerable to its effects and may be more susceptible to pressures to migrate out of agriculture and rural areas as a result [44]. Fortunately, adaptation to climate change in the agriculture sector and promotion of climate-smart agriculture practices may yield economic, social, and environmental benefits [45].

Despite the economic, social, and environmental importance of the agri-food sector in the MENA region, and its potential to deliver more benefits, the sector generally does not receive adequate attention or funding from policymakers. The agri-food sector is typically underfunded and rarely seen as a priority in major economic policy reform and investment programs. The agricultural orientation index—the ratio of agriculture share of government expenditures to agriculture share of GDP—is less than 1.0 in every country for which data is available, excepting Qatar (Table S2) [46]. The neglect of the agricultural sector in terms of public expenditure and foreign direct investment (FDI) has contributed to weak investment in agricultural research and poor performance of public extension systems in many MENA countries.

MENA countries range in the extent to which their respective agricultural sectors enjoy the support of favorable government policies or face legal and regulatory constraints to growth. According to the Enabling the Business of Agriculture index, the best performer in the region is Morocco, trailed by Jordan and Egypt; Tunisia, Sudan, and Iraq perform less favorably, though all countries have room for improvement to enable the growth and performance of their respective agricultural sectors. Data is unavailable for the remaining countries of the region (Table S2) [47].

3.2. Contribution of Digital Technologies to Agri-Food in MENA

Applied within the agri-food sector, digital technologies can promote long-term development by enhancing the sector's economic, social, and/or environmental sustainability. Below, the most significant potential contributions of digital technologies to agri-food in MENA are reviewed. Current, illustrative examples from the MENA region are noted according to their primary contribution; although digital technologies may indeed be multi-functional and contribute to more than one sustainability pillar simultaneously, this is necessary for organizational purposes. Selected illustrative examples are presented in Table 1; Table 2 within the appropriate sub-sections below; a fuller tabulation of examples of digital agriculture within MENA is presented in Table S3.

3.2.1. Economic Contribution

Digital technologies may enhance the economic contribution of MENA's agri-food sector via greater productivity and/or efficiency of resource use, whether physical, natural, or intangible such as data. The potential applications of digital technology are found on-farm, downstream in value chains, and within supporting e-government and public services.

Access to Land: Digital land information systems or e-registries can improve cadastral data and facilitate its access and use. Cadastral maps often differ from reality, impeding agricultural land market development and farm consolidation. Governments can improve existing cadastral maps via assessment, re-surveying land parcels, and updating digital cadastral maps. Digital technologies can also improve the functioning of land markets: Digitized land-use permits/registration and automated application processes can reduce times for filing and approval and increase transparency. Publicly accessible cadastral databases can increase efficiency of land markets by identifying available land and reducing registration costs [48]. In MENA, Morocco's National Land Registry now incorporates digital technologies to execute its functions [49].

Access to Machinery and Services: Digital platforms can improve on-farm access to agricultural machinery and services, particularly those imposing a high purchase price. Alternatives to direct purchase (e.g., leasing arrangements, contract-based provision, and/or cooperative approaches) may facilitate adoption, especially by smaller farmers [50]. Digital platforms can create efficient new markets for machinery rental by providing more affordable access to physical capital for smallholder farmers and employing underused assets by matching suppliers of machinery rental services with potential customers. The marginal cost of matching buyers and sellers through digital platforms is extremely low; therefore, platforms have the potential to reduce unit costs of machinery rental services through saved transaction and search costs [6,51]. Examples include mobile platforms to deliver tractor services and to connect animal health and veterinary service providers to small livestock operators. Within MENA, the Moroccan Agricultural Development Agency has since 2020 expanded the functionality of Attaisir—a farmer-focused system that aims to ensure sugar production for the domestic market—to enable remote monitoring of a fleet of 2000 GPS-linked agricultural machines and respect social distancing rules in light of COVID-19 [52].

Input Efficiency: Digital technologies can improve the quantity and quality of agricultural output while using less inputs (e.g., water, energy, fertilizers, and pesticides) and increase efficiency by performing farming practices remotely [6]. Crop yields could rise significantly by 2050 with the introduction of precision agriculture technologies, with an 18% yield increase due to precision fertilizer application, 13% due to precision planting, 4% due to precision spraying, and 10% due to precision irrigation [53].

Opportunities for improved water efficiency are critical for MENA. More water-efficient agricultural production is an important goal for water-scarce countries, but the use of partial productivity measures ("crop per drop") can be misleading. Moreover, farmers rarely seek to maximize the crop per drop measure in their production decisions. However, efforts to improve the allocation of water to more efficient uses could, even under conditions of climate change, yield better economic performance [45]. Smart irrigation systems that incorporate IoT and remote sensing technologies are one option to achieve more water-efficient agricultural production that accounts for farmer incentives. High-resolution satellite images combined with specific algorithms can determine spatial and temporal variability of agricultural water and land productivity. In field, remote sensors can measure water use and monitor net groundwater withdrawals; the resulting data can inform targets for sustainable irrigation water management and allocations to system users. Farmers' or landholders' water pumps can then be integrated into smart irrigation systems, allowing for real-time metering and remote shut-off if a water user exceeds a water allocation. Digital applications can allow farmers to use their mobile phones to control their irrigation pumps remotely and save time, energy, and water [6,54]. More efficient use of irrigation systems can also reduce the energy needed to operate those systems, with corresponding GHGE savings [11]. Smart irrigation systems with optimized fertigation could be particularly beneficial for MENA countries in view of current water scarcity, inefficient water use, and soil degradation. In fact, such systems are already in use in some areas. For example, in Jordan, digital technologies have been adopted to estimate evapotranspiration and monitor agricultural water use, including within irrigation systems [15]. This and similar examples are presented in Table 1.

Farm Management and Decision-Making: Higher quality agronomic data, weather data, and price information can improve farmer decision-making and management, ultimately increasing farmer profits and incomes, and this data can be recorded, analyzed, and disseminated more rapidly and more widely through the use of digital technologies. Access to information can also promote the inclusion of marginalized rural producers in markets, as when female farmers benefit from tools that encourage knowledge and information sharing [6].

Table 1. Precision agriculture for input use efficiency: illustrative examples of current application in Middle East and North Africa (MENA).

Country	Illustrative Examples of Precision Agriculture for Input Use Efficiency
Egypt	• Tomatiki is a start-up in the area of precision agriculture applying smart irrigation solutions [15,49]. • Innovation is a start-up producing large-scale, automated fish feeders for the fishery sector [15].
GCC	• ICARDA has developed digital technologies for precision management of date palm plantations [15].
Iraq	• Digital technologies have been adopted to support the application of drip irrigation [15].
Jordan	• Digital technologies have been adopted to estimate evapotranspiration and monitor agricultural water use, including within irrigation systems [15].
Lebanon	• The wine industry has adopted digital technologies including drone- and sensor-based IoT to assess growing conditions, water stress, vine performance, and disease [15].
Saudi Arabia	• The public Sustainable Agriculture Research Centre conducts applied research on innovative techniques for protected agriculture, including water use efficiency and pest management [15].
Tunisia	• Start-up companies including Ezzayra offer precision agriculture technologies [15,49]. Ezzayra is a private company offering management solutions in the form of sensors to monitor and regulate soil conditions (including irrigation and fertilization), as well as control irrigation leaks [55].
United Arab Emirates	• Responsive Drip Irrigation is a start-up company developing self-regulating irrigation technologies [56].

Extension Services: Across MENA, digital platforms for knowledge dissemination could play a useful role in improving the quality of extension services. Existing extension services are currently insufficient to meet farmers' needs in many countries, offering limited farm visits and outdated information that excludes new production technologies [26]. E-extension services (public or private) may address constraints of traditional extension services and provide cost-effective ways to reach more farmers. E-extension can supply farmers with real-time access to relevant data and information to support sustainable farming practices, climate-smart solutions, and market access [6,51], with the ability to customize services based on farmer characteristics such as location, educational background, or financial situation. Digital technologies that incorporate use of photographs or video—for example, to deliver remote pest and disease diagnostics—may complement to field advisory visits but may not yet offer a complete substitute. In the context of COVID-19, e-extension services could expand to include new information on personal hygiene and safe handling of food products [57]. In Lebanon, the Facebook group *Izraa* was established by agricultural engineers to offer free advice, tutorials, and questions-and-answers for a variety of agricultural contexts (rural or urban, high- or low-technology) during the pandemic and has since reached more than 100,000 members [58].

Meta-analyses report that the transmission of agricultural information through mobile technologies can increase yields by 4% and adoption of recommended agrochemical inputs by 22% [59]. Benefits of e-extension services significantly exceed the costs, and this gap should widen further as the cost of information transmission continues to fall. Nevertheless, evaluation is still ongoing as to which of the various forms of agricultural e-extension services work best and under what conditions [6].

Resilient Production and Risk Mitigation: Digital technologies may support improved agri-food sector performance throughout or in response to shocks or crises, whether natural or manmade. The combination of remote sensing and big data applications is increasingly used to enhance agri-food management and to mitigate risk. These applications include automated early warning systems for crop or livestock health linked to threats from weather, pests, and diseases, which can facilitate proactive and timely management responses as well as generate crop yield projections [51]. Applications can be used by farmers and along the entire value chain including input suppliers, logistics providers, market actors, and policymakers [26,60].

Digital technologies can also mitigate financial risks. Access to tools targeting weather-related risks is limited or out of reach for many farmers and small-to-medium size businesses in MENA. Remote sensing technologies can reduce the monitoring costs of traditional insurance contracts, improve the contracts available to smallholder farmers, and reduce their costs [26]. Elsewhere, smart contracts—blockchain-enabled arrangements that contain all information about the contract terms and execute all envisaged actions automatically—can provide a risk mitigation tool that is flexible, low-cost, secure (traceable and irreversible), and highly customizable to a variety of risks and payouts, with minimal transaction costs and without the need for third parties. Smart contracts are already in use for weather-based crop insurance, with a number of digital tools reaching the market in recent years [61]. The continued development and spread of these technology-backed product offerings will require legal-regulatory reforms (both agricultural and financial) in many MENA countries [26].

Access to Finance: The digitization of financial transactions and payments can foster inclusion of unbanked farmers. Digital payment systems, mobile phone-based financial and insurance products, and big data analysis can reduce the cost of credit. A minor share of smallholder farmers has access to formal credit in many MENA countries, but big data and advanced analytics can reduce the cost of establishing their creditworthiness and assessing insurance risk [51]. These reduced costs may translate into lower interest rates for farmers, expanding access to financial services. Digital solutions can also help smallholder farmers to access family and friends' savings in times of need [26]. In addition, digital financial solutions have been shown to have a positive and significant effect on household input use, agricultural commercialization, and household income (e.g., [51,62,63]). Over the long term, farmer use of e-wallet services can pave the way for adoption of other digital financial services such as input credit, agricultural insurance, and savings accounts [64]. As interoperability (the ability to both pay and receive funds across banks, internet, and mobile platforms) becomes standard, the use of digital payments is facilitated. Within MENA, digital applications are already targeting access to finance, with digital payments systems reported in Jordan, Lebanon, and West Bank and Gaza (see Table S3). In Tunisia, AHMINI targets rural women's inclusion in social protections and expands their access to insurance against work accidents, health insurance, and retirement income [15].

Market Access and Information: Digital marketplaces and e-platforms for agricultural products can link producers directly to consumers, shorten agri-food value chains, expand producers' access to new markets (usually within national borders), reduce food loss, and create new business opportunities for small agricultural producers and small- and medium-sized enterprises (SMEs) [6,65]. Lowering information-related transaction costs through digital technologies helps to expand access to input and output markets and reduce information asymmetries and inefficiencies caused by reliance on market intermediaries [66,67]. Digital marketplaces may improve price transparency, which is particularly needed in markets marked by obscure pricing that is subject to manipulation, for example wholesale markets where traders can exploit information asymmetries to the detriment of farmers [26]; however, digital marketplaces may not prove a panacea if AI and data analytics in fact facilitate price targeting or manipulation [68]. Because e-platforms can match producers and consumers at nearly no cost, they have tremendous potential to overcome past market failures, expand market access, and restructure value chains. To date, the application of e-platforms or e-commerce for international transactions for agri-food products has been hampered by a lack of explicit international guidance regarding e-commerce, food trade, and consumer protection to assist national regulators [69].

An illustrative example comes from Oman. In partnership with the Oman Technology Fund, the government of Oman introduced the Behar digital auction platform to sustain aquaculture production despite the disruption of COVID-19 to traditional, in-person market operations. The platform also facilitates electronic payments for registered accounts. The platform has sustained market activity during COVID-19, while ensuring proper health and safety measures are respected [70]. This and other examples of digital technologies supporting expanded market access and information in MENA countries, including digital marketplaces and e-commerce, are presented in Table 2.

Table 2. Market access and information: illustrative examples of current application in MENA.

Country	Illustrative Examples of Digital Technologies for Market Access and Information
Egypt	• Freshsource is an e-commerce, business-to-business platform linking horticulture producers to vendors in Cairo [15,49]. • Freshfarm is a start-up working as an intermediary between farmers and consumers, facilitating direct purchases to raise farmer incomes and reduce consumer prices [15].
Jordan	• Websites operated by large wholesale and producer associations (Wholesale and Vegetable Market of Greater Amman Municipality, Jordanian Exporters and Producers Association for Vegetables and Fruits) share market price information, as well as export standards, to support both farmer incomes and export performance [15].
Lebanon	• The AgVisor application allows farmers to compare crop market prices and to access a director of actors across value chains [15].
Oman	• The Behar digital auction platform provides an alternative to traditional, in-person market operations during the COVID-19 pandemic and facilitates electronic payments for registered accounts [70].
Tunisia	• Herundo delivers e-commerce services to the National Olive Oil Exporter Association. Its business-to-consumer platform seeks to expand access to export markets, reduce transaction costs, capture economies of scale, and improve branding [15,49].

Transaction Costs: Digital technologies can improve agricultural supply chain organization and management by optimizing aggregators' performance. Smallholder farms increasingly turn to aggregators such as farmer cooperatives and organizations that use digital tools to improve collection, transportation, and quality control [65]. Gathering producers, aggregators, and buyers on one platform increases transaction volumes, raises prices for farmers, creates enterprise opportunities for aggregators, and delivers traceable and better-quality produce to buyers. Digital platforms have been developed to collect and aggregate data on farm production, which networks of village aggregators and buyers then use to market and sell produce. Other applications use competitive bidding to link transport providers and producers at optimal prices [26].

Transparency and Traceability: Food sensing technologies, blockchain (distributed ledger), and e-platforms can be used to improve value chain transparency and traceability [6]. Barcodes and digital scanners to improve traceability have been in increasing use since the 1970s, enhanced by the introduction of higher-capability coding systems (e.g., DataBar, RFID chips) [71]. More recently, distributed ledger technologies such as blockchain have allowed for improved product traceability and integrity, contract certainty, and compliance with SPS requirements [61]. Blockchain technology prevents data from being improperly altered, which helps to ensure transparency and thereby build trust among retailers and consumers located at the end of decentralized supply chains [72]. Improved traceability of food products can reduce the lost productivity and medical expenses associated with inadequate food safety, which imposes costs estimated at $110 billion annually across low- and middle-income economies [51,73].

Food Loss and Waste: Digital technologies have the potential to reduce food loss and waste in food systems. For example, blockchain-enabled traceability could reduce food loss by 1–2% within the global food system by 2030 [74]. Online, blockchain-supported marketplaces and smart food loss management systems have been designed to facilitate the sale of surplus food directly to end-consumers either as food or for non-edible uses (e.g., compost, alternative processing) and avoid its disposal [75]. In Egypt, e-commerce technologies connecting farmers to modern markets and supporting sustainable agriculture practices have enhanced their efforts to tackle food loss and empower farmers during the COVID-19 pandemic [76].

Food Safety Compliance and Control: Digitally enhanced traceability could help producers to expand exports to more demanding and more lucrative markets that impose more demanding food safety standards, such as European Union countries. Producers can adopt digital technologies to ensure compliance with maximum residue levels for pesticides and with standards preventing microbial contamination. If maintained over the longer-term, digital traceability systems could assist and guide producers to undertake needed improvements in the quality, food safety, and sustainability standards of their production. Moreover, moving directly from rudimentary solutions to digital technologies for improved traceability may be an opportunity to leapfrog intermediary technologies [26].

Public actors can use digital technologies including DLT to improve food control systems. Food safety data collected via remote technologies can inform the development of risk-based strategies for inspection along food chains, which is a more cost-effective approach to food safety control than universal inspection. The use of e-certification for electronic transmission of SPS data can improve the accuracy and reduce the cost of international food trade, as compared to traditional paper-based systems [69].

Data Collection and Dissemination: The use of digital technologies to collect and disseminate available data on a timely basis has been identified as an opportunity in multiple MENA countries, especially where data gaps are large. Remote sensing may offer a powerful and cost-effective means to assess agricultural production in inaccessible areas, such as conflict-affected areas, across a wide scale and over time. Efforts to use digital technologies to improve both the collection and the publication of accurate and timely data specific to the agriculture sector could support the development of evidence-based policies. The timely provision of accurate data could also help identify specific challenges facing the agriculture sector. In the context of COVID-19, digital delivery of market information and pricing platforms could allow for transparency while reducing physical contact. Frequent digital monitoring and/or real-life crowdsourcing of food prices can allow taking legal action against any vendor manipulating prices during the crisis [26]. For example, Qatar's Ministry of Commerce and Industry maintains a website sharing daily price information for major food commodities (fish, fruit, and vegetables) [77] and has operated a multi-channel consumer complaints line as a means to monitor and control price hikes linked to both trade embargoes as well as the COVID-19 pandemic [78].

Monitoring and Evaluation: The adoption of digital technologies for agricultural data generation can support more cost-effective monitoring and evaluation of government programs. For example, satellite imagery provides timely, consistent, and unbiased information on whether agricultural investments and development projects are sustainable and effective [51]. Enhanced aerial imagery allows plot-level monitoring; drone-based inspections; and sensor-based plant, water, and soil analyses. Remote sensing technologies significantly reduce the cost and time required to monitor land cover and land use, elevation, soils, and watersheds, especially in remote areas [2]. In conflict-affected areas, satellite data can support intervention targeting, analysis, and advance planning [26].

3.2.2. Social Contribution

Employment: Digital technologies—notably automation and robotics—have a wide range of applications in the agri-food sector, ranging from surveying to planting to livestock monitoring to food delivery. These applications could deliver a dizzying array of social impacts including safer working conditions but could also reduce labor requirements with corresponding impacts on employment [10]. Indeed, the application of digital technologies is often assumed to displace labor within the agriculture sector. This concern may be overstated as displacement may apply only to selected technologies, specifically digital technologies that can replace manual labor within capital-intensive agricultural operations. For example, robotic technology could replace manual labor for tasks such as weeding, harvesting, and milking. Other digital technologies may be labor enhancing, increasing the efficiency of agricultural labor and the productivity of agricultural operations in terms of lower production costs, higher yields, reduced loss, and higher revenues. Digital technologies can also enable (smallholder) farmers to upgrade their skills, encouraging inclusion of low-skilled farmers and helping enhance their productivity. Additionally, the knowledge needed to develop and operate digital technologies for agriculture may generate new employment opportunities. Thus, the modernization of the agriculture sector could create more productive, skill-intensive, and remunerative jobs in the agricultural sector and along value chains [6].

Digital Identification: The digital identification of farmers offers several opportunities for improved social outcomes. Identification provision can support the transition from informality to formality, linking farmers to their assets (land, livestock) and increasing access to financial services. Moreover, farmers' identification can support agricultural entrepreneurs and digital solution providers who currently invest roughly half of their initial business development efforts in profiling and identifying target farmers [6,26].

Subsidy Distribution and Social Safety Nets: Governments can use digital identification systems to more effectively target input and cash subsidies to farmers, create digital farmer profiles to improve service delivery, and open up new economic opportunities for the poor. For example, the Nigerian government applied an e-wallet digital payment program for subsidized fertilizers that reduced leakage compared to its previous subsidy system [79], increasing efficiency significantly. International organizations are similarly applying digital payments for efficient distribution of humanitarian and development assistance. In Jordan, a partnership between Making Cents International and BanQu has applied blockchain to deliver digital identification to vulnerable populations for facilitate delivery of social, financial, and health services [15]. Digital technologies can also facilitate the distribution of social safety net payments with improved efficiency. In a context such as COVID-19, the use of digital payments or e-vouchers can further reduce human contact and thereby preserve the health of beneficiaries and government employees.

3.2.3. Environmental Contribution

Reduced Use of Scarce Natural Resources: Through the application of digital technologies, the more efficient use of natural resources including water and land can, in theory, lead to use reductions and thereby more sustainable outcomes. However, this is not guaranteed: The optimization of resources such as groundwater may perversely lead to their expanded use if limits are not imposed, a phenomenon known as rebound use [80]. While precision agriculture and digitally-enhanced controlled agricultural production in MENA are reportedly motivated by water scarcity concerns [15], evidence of their net water impact is not currently available.

Reduced Use of External Inputs: On-farm, digital technologies including precision agriculture applications can achieve positive environmental effects through reducing excessive or inappropriate input (fertilizer, pesticides) use [6] that contributes to unnecessary soil and water pollution, energy use, or GHGE. However, a critical perspective of digital agriculture argues that it cannot deliver sustainable agriculture rooted in agroecological approaches, insofar as it still relies on the use of agrochemicals [12]. Despite multiple examples of precision agriculture across MENA (see Table S3), evidence on their ability to reduce the use of external inputs is not currently available.

Reduced GHGE: On-farm, precision agriculture can reduce in-field fuel use, use of nitrogen fertilizers, and land tillage, the latter two of which can have positive effects on carbon sequestration in soils. All three shifts may contribute to lower GHGE [11,12]. Downstream, ICT and sensors may optimize transport logistics within agri-food chains, reducing fuel usage and delivering environmental benefits via reduced carbon footprint. Whether e-ecommerce can similarly deliver GHGE savings depends on the efficiency of transportation, and the available empirical evidence of net impacts is mixed [11].

Biodiversity and Ecosystem Services Impacts: Proponents of precision agriculture argue that the improved efficiency offered by these technologies can reduce pressure on natural resources and limit the clearing of land [12], which can have positive effects on the maintenance of biodiversity and ecosystem services [18]. Additionally, technology-assisted reductions in the use of chemical pesticides and herbicides may slow the development of resistance among animal and plant pests [13]. Moreover, empirical evidence shows that precision agriculture can deliver higher crop yields with positive or at least neutral impacts on ecosystem services (notably water flow regulation and soil structure and fertility enhancement), versus conventional intensive farming techniques [81].

Aggregate View of Agriculture and Evidence-Based Policies: Insofar as sustainable agri-food systems are knowledge-intensive [11], they may rely on extensive data and information derived from a range of sources, including digital technologies such as ICT and remote sensing. Over time, the accumulation of significant data from digital technologies could provide a clearer understanding of the impacts of intensive agriculture and the current industrial food system on the environment, as well as the effects of climate change on agricultural production. This, in turn, could inform a shared understanding of sustainable agriculture and policies to promote it, or could motivate action to combat climate change [82]. For example, monitoring through satellite technology could enable governments to assess how agricultural practices affect the ecosystem, develop better regulations, enforce sustainable land management practices, and address vulnerability to climate change [51].

3.2.4. Summary of Contributions within MENA Sub-Regions

Gulf Cooperation Council (GCC): The GCC includes Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. According to a recent analysis by the FAO, the GCC region is most advanced in the adoption of (largely but not only public) e-extension services with respect to digital agriculture technologies, though farmer uptake may be limited. Public authorities in Qatar similarly offer several e-government solutions to facilitate agricultural service delivery, such as for veterinary health certificates. Remote sensing (satellite imagery) and crop modelling have been adopted for high-value export crops including date palms, with a focus on improved farm management, pest and disease prevention, and irrigation management. Another key area for the application of digital technologies in GCC countries is within controlled-environment agriculture (e.g., greenhouse production) [15], reflecting the challenging natural conditions for agricultural production.

The COVID-19 pandemic has pushed GCC countries to boost digital agriculture, with notional and concrete advances reported in 2020 [83]. Significant investments in agricultural technologies—including digital agriculture—have been announced across the GCC [84,85]. Notable are sizeable investments by the sovereign wealth funds of Kuwait and the United Arab Emirates [56]. ICARDA has established more than 2000 plots for soilless agriculture using digital applications for remote monitoring and control across the GCC sub-region [86]. Despite the limited advance of digital agriculture thus far, public actions have signaled support for further adoption. Selected GCC countries have hosted events to exchange knowledge, to launch collaborative efforts (e.g., a joint FAO-KSA-UAE regional kickoff workshop for the Research Technology and Innovation project), and to jump-start investment in emerging digital technologies (e.g., UAE hosted an international conference for agricultural technology innovation) [87].

Hurdles limiting the adoption of digital agriculture by GCC farmers include a lack of awareness, ill-suited digital solutions to farmer needs, and farmers' disinterest in digital agriculture [15].

Maghreb: A recent diagnostic of digital agriculture in the Maghreb determined that it has a limited presence, though there have been interesting developments [49]. The FAO has reported that Egypt, Morocco, and Tunisia have begun to adopt digital agriculture technologies including precision agriculture (particularly for irrigation), e-extension services (both public and private), e-finance services for farmers, and e-commerce applications to expand market access, although their development is not consistent across countries. For example, while Morocco has well-developed e-finance services, e-commerce is nearly non-existent [15]. As for e-government, Egypt's public efforts have met with limited citizen adoption (only 2% by 2019) [7]. Little or no information has been reported regarding digital agriculture in other Maghreb countries. In Algeria, precision agriculture has been touted as an important contribution to large-scale farming projects in the south of the country [88], but details about current implementation are unavailable. Similarly, Sudan's Gedaref Digital City Organization has announced ambitious plans to apply digital technologies to improve agricultural production [89], but the status of these plans is unknown. In the case of Mauritania, the gap in information is unsurprising given barriers including exceptionally high costs of mobile and internet services and low levels of adult literacy [7].

Maghreb countries have accelerated this adoption during the COVID-19 pandemic. For example, in mid-2020 Egypt announced a cooperation protocol between its Ministry of Agriculture and Land Reclamation and the Ministry of Communications and Information Technology to develop irrigation practices incorporating AI, ICT, and remote control for enhanced water resource use and management [90].

Hurdles to the adoption of digital agriculture in Maghreb countries include farmers' resistance to innovative technologies [55], a lack of digital services and broadband in rural areas, legal and regulatory obstacles, and logistical and administrative barriers to entry [49,76].

Mashreq: Evidence shows that adoption of digital technologies within the agri-food sector in the Mashreq sub-region (specifically Iraq, Jordan, and Lebanon) is at early stages, generally led by high-value and export-oriented agricultural production. Nevertheless, digital technologies show promise to advancing the transformation of the agri-food sector in Mashreq. Indeed, governments have at least acknowledged this potential, and the digital transformation agenda already features in the respective countries' economic and sector development strategies [26].

As in other sub-regions, the advance of digital agriculture has accelerated since COVID-19. For example, Jordanian companies and start-ups are increasingly offering technological services to meet the needs of the agricultural sector [91].

The adoption and development of digital agriculture in Iraq, Jordan, and Lebanon are limited by gaps in awareness and understanding of digital technologies and their potential use within the agriculture sector, low levels of digital connectivity among farmers, mismatches in the language used by digital technologies (English) and by some farmers, and inadequate access to finance and data [26].

Conflict-Affected States: Little information is available on the status of digital agriculture in Somalia, Syria, West Bank and Gaza, and Yemen. Notable examples demonstrate the ability of digital technologies to respond to conflict-related challenges, such as the application of remote sensing to estimate agricultural production and conflict-related impacts on agricultural performance in Syria [92,93] and e-learning solutions for agricultural education [94].

Small Countries: Little information is available to suggest a robust adoption of digital agriculture in Comoros or Djibouti. For example, a recent, comprehensive review of the agricultural sector in Comoros made a single mention of digital technologies, highlighting the lack of mobile money or digital credit, which limits access to finance in rural areas [95].

3.3. Challenges to and Risks of Digital Technology Adoption in Agriculture in MENA

3.3.1. Challenges

The adoption of digital technologies within the agri-food sector is not automatic, and a number of hurdles have been identified. An exhaustive review of the conditions and drivers of successful technology adoption and application is beyond the scope of this article, but readers are referred to existing works in the areas of precision agriculture [50,96,97]; and big data [98,99]. Several of the key hurdles within the MENA region are reviewed here.

Cost and Profitability: High purchase, operating, and/or maintenance costs can impede the adoption of digital technologies, particularly by smaller farmers or SMEs who may lack access to credit or other financial resources [100]. Moreover, the financial benefits of adoption must be clear: Evidence shows that profitability is a fundamental condition for the adoption of new technologies by farmers, particularly smallholder farmers [96,101].

Technical Knowledge or Expertise: A lack of technical expertise to understand or utilize digital technologies (or the data that they generate) can restrict their adoption, particularly by smaller farmers or those on the weaker side of the digital divide [82].

Suitability to Local Conditions: Digital agriculture resources have often been developed outside of the MENA region, adapted to the needs of farmers in other areas or production systems, and are often available (only) in English, which can limit their use and uptake in MENA countries. For successful adoption and application, digital technologies and services need to be well suited to application in local conditions, including languages [102]. For example, e-extension services must provide timely, localized, and customized information addressing specific farming concerns in a comprehensible format and in Arabic or another relevant local language [51]. Low-performance, frugal innovations may be developed to meet the capacities and needs of less sophisticated or smaller actors [96].

Complementary Technologies: The absence of complementary technologies—notably minimum data system or internet capacities—can challenge the adoption of digital technologies in agriculture [98]. For this reason, digital agriculture applications that can operate at a low and medium internet connectivity are especially well suited to connect smallholders along agri-food value chains. Even in low-connectivity, rural environments, many (off-line) digital agriculture technologies can be deployed to support poor or illiterate farmers or marginalized groups with limited access to information and markets [51].

Underlying Constraints: The application of digital technologies alone may have a limited effect on expanding market access to farmers, unless underlying constraints are simultaneously are addressed. For example, in Lebanon, the creation of digital platforms for pricing information did not address the fact that farmers were engaged in complex relationships with both input dealers and wholesale traders. Crop farmers benefitted from informal credit arrangements with both input suppliers, who provided seeds, fertilizers, etc., on credit and received payment at the end of the agricultural season and with wholesale purchasers, who paid up-front upon receipt of the produce. These informal financial arrangements limited the ability of a farmer to shift among input suppliers or wholesale purchasers, regardless of the ability of farmers to gain price advantages elsewhere in the market [26].

3.3.2. Risks

As any major technology change, the digital transformation of the agri-food sector incurs risks—or even negative future outcomes—that must be understood, acknowledged, and managed [3,17]. The various risks may relate to the use of the internet, including inequality in access and affordability; concentration of market power of e-commerce platforms, social networks, and search engines; data privacy and consumer protection; and cybersecurity [103]. Several of the potentially most critical risks for the MENA region are highlighted below.

Labor Displacement: Digital technologies may displace agricultural labor with labor saving technologies [1,104]. Such technologies may include harvesting robots, driverless tractors, sprayer drones, AI to manage chemical and fertilizer application, and precision dairy farming. Conversely, the adoption of digital technologies to support automation within the agriculture sector could create high-skilled, high-paying jobs such as managing and maintaining robots or analyzing and interpreting data collected from digital sources and AI [104].

Adoption Gaps and Widening Inequality: Given the differences in the challenges they face, or the extent to which they face them, smallholder and larger, commercial farmers have different potential for adoption of digital technologies. It is important that small and large farmers and businesses alike should benefit from digital innovation [82]. Furthermore, digital innovations should not deepen the inequalities that typically disadvantage women, youth, refugees, and other vulnerable groups who may not have equal access to technologies and skills.

Non-Adoption: Conversely, there are implications for MENA countries associated with the non-adoption or low adoption of digital technologies [3] as their agriculture sectors may lose competitiveness and fall further behind other countries. Already the lack of competitiveness (not solely due to non-adoption of digital technologies) has limited the ability of agriculture producers in Iraq, Jordan, and Lebanon to sell their products to lucrative export markets [26]. In MENA countries that will pursue digital agriculture, public and private actors alike will need to partner and keep pace with fast-moving technology actors [49].

Data Ownership, Privacy, and Security: Farmers and operators may have valid concerns over the ownership, privacy, security, and equitable use (and re-use) of the data produced from digital technologies, and these concerns can limit their willingness to adopt them for use on their farms [82,99,105].

Resource Use and Waste: While digital technologies may offer important environmental benefits, including through the optimization of scarce inputs including water and energy, they may also generate new streams of resource use and waste, including GHGE related to increased energy use [10], energy-intensive data storage or the waste of electronic or digital materials. The environmental impacts of digital technologies adopted by the agriculture sector in MENA are as-yet unknown. The importance of this impact on the development of digital agriculture and opportunities to mitigate these impacts remain areas for future inquiry [26].

4. Discussion

The evidence reviewed above amply demonstrates that the digital transformation is applicable to the agri-food system at all stages of the value chain. Digital technologies such as precision agriculture, e-extension services, and digital markets matching inputs, producers, and/or consumers have tremendous potential to increase productivity on farm and within agri-food value chains, improve resource use efficiency and support adaptation to climate change, and thereby promote sustainable development within MENA. Moreover, digital technologies can help to reduce cost and increase efficiency and transparency of all public services, including those related to the agri-food system, for example by digitalizing land tenure mapping and registration, subsidy distribution, weather forecasting, and water resource management [6].

The potential economic contribution of digital technologies is presented in the literature more than either the social or the environmental contribution. While there is significant concern that digital technologies will exacerbate inequalities or contribute to labor displacement, the evidence appears to be mixed, perhaps due to the relatively early stage of digital technologies and the longer-term scale on which social phenomena play out. Similarly, the examination of potential applications of digital technologies for improved environmental sustainability—to reduce if not eliminate damaging environmental impacts as well as to generate benefits such as ecosystem services [106]—within the agriculture sector is only emerging. Moreover, evidence on whether this potential environmental contribution will materialize is in its early stages [17]. This observed lag of the social and environmental dimensions is consistent with previous research [3,17].

Neither the adoption nor the benefits of digital technologies are guaranteed, and digital technologies may not fully deliver the promised transformation for the agricultural sector [17]. Digital technologies could accelerate the depletion of natural resources and increase the absolute value of greenhouse gas emissions from agricultural production—the so-called "rebound effect" because efficiency gains could lead to increased use [80]. In terms of equity, the use of advanced digital technologies in the agriculture sector may widen the digital divide, if smallholders are unable to make use of these technologies due to a high cost and specialized skills needs [82].

Across MENA, there are some notable examples of where digital technologies have been introduced into the agri-food sector, marked by clustering around public services, high-value, export-oriented value chains (in Maghreb and Mashreq), and intensive production to satisfy local market demand (in GCC). The lack of evidence and reports of adoption suggests, unsurprisingly, that the digital agriculture transformation is less advanced in conflict-affected and less developed countries.

4.1. Policy Implications and Priorities

With the appropriate policy support, the adoption and application of digital technologies within MENA's agri-food sector could help to transform it into a source of improved economic growth, social inclusion, and environmental sustainability. Without the appropriate policy support, digitalization may disrupt the sector in adverse ways such as reducing employment, widening inequalities, and further exploiting already scarce resources. Policymakers should take prompt, comprehensive, and thoughtful action to ensure that the digital transformation of agriculture is to the collective benefit of both stakeholders and societies. Policies must not only foster the adoption of digital technologies in MENA, but also address concerns around equity of access, transparency of use, data protections, and protections against adverse labor impacts. Public action should respond to the actual and urgent needs and should build on the most promising opportunities for digital transformation of agriculture in the region as reviewed above.

Vision and Strategy for Digital Agriculture: Few if any countries in the MENA region have a comprehensive vision or strategy for digital agriculture [7]. Accordingly, they those that have not yet done so, should develop a vision and strategy for the role of digital technologies within their respective agricultural sectors and wider agri-food systems. Such visions and strategies should highlight the potential contribution of digital agriculture to outcomes like food security but also acknowledge that technology-based, production-focused solutions are only partial and will not resolve parallel concerns such as problematic food access and distribution [3,5,18]. Moreover, responsible policymaking should acknowledge and articulate the trade-offs associated with innovative technologies such as digital agriculture [10]. These visions and strategies should reflect stakeholders' and the wider society's ethical perspectives on the application of digital agriculture [17,82].

Strategies aiming to promote the adoption of digital technologies at the production level should consistently consider the role of both upstream and downstream contexts and actors. Such an approach would reflect the shifting agri-food landscape: "Increasingly, the urban market, the food industry firms that mediate access to the urban market, input supply chains, and agribusiness firms that determine the development of input supply chains, set the market incentives and conditions for the affordability and profitability of new farm technologies, and thus their adoption" [107] (p. 48). This consideration is particularly relevant in MENA, given the greater dynamism of downstream segments of the agri-food sector in recent decades [22].

Strategies should be complemented with appropriate action plans and targets for implementation. Strategies, action plans, and targets should be rooted in the concrete needs of potential users and in a clear understanding of both the barriers and incentives to the adoption of digital technologies by farmers and other actors along the agri-food value chain. Within these strategies, interventions must help ensure that small farmers and small businesses benefit from digital innovation in the same way as larger operators. Similarly, gender-sensitive approaches are needed to ensure that disparities and women's lack of empowerment within the agricultural sector are addressed or, at a minimum, not widened [26].

Knowledge and Skills Development: Public actions to expand and enhance appropriate knowledge and skills can facilitate the adoption and/or development of digital agriculture technologies, including via improved education [101]. Farmers and agricultural stakeholders may require support around basic digital literacy, business and farm operations management, and the use of customer-facing technologies like digital marketplaces. Within agricultural universities and vocational training programs, exposure to digital technologies within the curriculum can improve adoption, adaptation, and development of locally appropriate technologies. Elsewhere, entrepreneurs and start-ups innovating in the digital technology space may require knowledge and skills around business development and finance, as well as a better understanding of the challenges facing the agri-food sector [26]. Education initiatives to facilitate the adoption of digital technologies must balance the optimization of resources (e.g., targeting actors who show higher likelihood to adopt) [97] with attention to widening disparities.

Data Ownership, Use, and Privacy Protections: To address serious and valid concerns over data ownership, use, and privacy linked to digital technologies, policies can help to establish and clarify the rights of different stakeholders. While such policies are typically not specific only to agricultural technologies or data [99,108], there is a need to balance the privacy and legal protections for the entities (farmers and firms) that generate data, with the potentially tremendous benefits to be gained from the aggregation and analysis of data and application of the resulting information. Indeed, open access to large datasets could facilitate critical evaluation of smart farming, or even enhance entrepreneurship and economic activity [82]. Policies can help to set the frame for positive feedback loops, in which good governance builds user trust in digital technologies. Protections for data integrity can result in greater trust in that data and its application in evidence-based policies and programs [26]. Due to the rapid evolution of digital technologies, public actors should track sector developments to ensure that policies and regulation around digital agriculture reflect current challenges and needs.

Support and Enabling Environment for Private Investment: Both the public and the private sectors will play a role in the digital transformation of agriculture, with private actors playing a particularly important role in developing and adapting digital technologies. Public policies can facilitate private investment in digital agriculture—as well as the mobile and internet infrastructure and services necessary for digital technologies—by offering a supportive enabling environment, investment incentives, and partnership opportunities. Public policies can also foster an innovation ecosystem for digital agriculture technologies and innovation, providing information, networking opportunities, and incubation and acceleration services where the private sector has yet to do so [7,26]. Policies should seek to balance an environment that supports profitable investment opportunities with protections against market power concentration that can stifle innovation [7].

Non-Digital Reforms and Investments: Policy action that is specific to digital technologies may not be sufficient to unlock the transformation of the agricultural sector, if complementary reforms and investments addressing non-digital barriers to the sector are not also addressed [7]. For example, digital technologies that facilitate logistics and target reduced food loss will offer only partial improvements without investments to improve transportation, storage, and power infrastructure, which are badly needed in many lower-income MENA countries. To deliver on the promise of digital technologies to expand access to finance to small farmers or rural areas, improvements to financial sector laws and regulations may be required [26]. Extending market access via e-commerce platforms may require the establishment or improvement of digital payment systems, which build on banking and telecommunications policies as well as consumer protection frameworks [109].

Public Supply of Digital Agriculture Services—E-Government and E-Extension: The public sector can not only foster the demand for digital technologies but can also adopt or supply them directly. Digital technologies may improve efficiency, reduce cost, and increase transparency and accountability of many public services—not only agriculture. Within the agri-food sector, e-government could deliver statistical data collection and dissemination; open data platforms for land, soil, weather, and market price data; e-extension services; digital identification for farmers and other stakeholders; land e-registries; and public subsidy payments [26]. Successful e-government services require administrative capacity for design and management, as well as commitment to the often slow pace of user adoption [7]. Of note, through e-extension, the public sector can support the use of digital technologies that enhance the efficient use of scarce resources (e.g., irrigation water) and optimize the use of inputs (e.g., fertilizer, pesticides) to support productivity, efficiency, and environmental sustainability. E-extension can particularly target the needs of smallholders, addressing their risk aversion, information gaps, and mistrust of technologies or their promised benefits. Techniques including digital piloting and knowledge exchange may be well-suited to the needs of small farmers [26].

4.2. Research Contributions and Conclusion

This article has sought to contribute to the topic of digital agriculture in the MENA region in several ways. First, this article briefly reviewed the key features of the agri-food sector and key challenges to its sustainability including scarcity and inefficient use of natural resources, suboptimal agricultural management practices, poor market functioning, inefficient markets, and limited access to finance. These challenges are compounded by conflict and social unrest, climate change, and insufficient public support for the agri-food sector.

Second, we reviewed the potential contribution of digital agriculture to address these challenges and found significant evidence of positive impacts across all three dimensions of sustainability. While the literature has more clearly mapped and established the economic contribution of digital agriculture, the social and environmental contributions promise to be significant and highly needed within the region.

Third, a review of the current status of digital agriculture in the MENA region generally finds an early stage of adoption, though with some notable sub-regional patterns. Digital agriculture in the GCC is oriented to ensuring a minimum level of domestic food production to ensure social needs, while in Mashreq and Maghreb digital technologies are being applied for both local and export market destinations including EU and GCC. Conversely, digital agriculture in conflict-affected countries appears to be more practically oriented to conduct or deliver basic services at a distance, while maintaining human safety. This review further highlights a gap in knowledge around the state of digital agriculture in several countries of the region, including lower-income countries (e.g., Mauritania, Sudan), small states (e.g., Comoros, Djibouti), and conflict-affected states (e.g., Syria, Yemen). While the absence of information would suggest that digital agriculture is not well developed in these parts of the MENA region, the status of digital agriculture in these countries nevertheless remains an area for future research.

From a thematic perspective, the application and introduction of digital technologies to the agri-food sector—globally and in MENA countries—have tended to focus on economic objectives, with less contribution to addressing the social and environmental challenges facing the agri-food sector. Indeed, evidence of the environmental contribution of digital agriculture in the MENA region is as-yet missing. Though expected, this gap suggests that the application of digital technologies to address the significant social and environmental challenges facing the agri-food sector in the MENA region requires prompt and careful consideration. Insofar as the countries of the MENA region have a responsibility to determine for themselves the future of digital agriculture that they wish for themselves, this consideration is timely.

COVID-19 has catalyzed the introduction of digitalization along the agri-food system, including in the MENA region. Whether this transition will prove temporary or permanent remains to be seen [9]. This introduction was not structured; rather, it was an organic response from market-based actors, rather than a public-led policy decision. This allowed for faster penetration and market-led response to needs, but the disadvantage is that this has been driven by profitability considerations. As a result, we need now to take stock of these experiences—to which this paper contributes—in order to mainstream these experiences into polices that foster inclusive economic performance as well as social and environmental goals, for a true contribution to sustainability.

Finally, this article proposes a number of policy implications and priorities for relevant stakeholders across MENA countries, to unlock the potential of digital agriculture towards sustainability. Policymakers are urged to expand their traditional, production-centric views of the agri-food sector to account for social and environmental considerations and to work towards a digital future in which the agri-food sector not only generates productive value but also delivers on social and environmental sustainability.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/6/3223/s1. Table S1: Search results from Web of Science for "digital agriculture" and "smart farming" in MENA countries. Table S2: Selected economic, social, environmental, and policy indicators. Table S3: Evidence of digital agriculture across MENA countries.

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