The role of digitalization on the way towards a sustainable agricultural sector in Colombia

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AFFIDAVIT

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ABSTRACT

The development of agriculture throughout history has had a profound impact on human lifestyles, enabling the establishment of settlements and leading to population growth through increased food availability. This has created an ongoing pressure to increase agricultural production to meet the world's demand for food. However, agricultural processes are not efficient, resulting in food losses that have negative environmental (e.g., degradation of natural resources and pollution), social (e.g., reduced food security and nutrition) and economic (e.g., reduced farmer income) impacts. The purpose of this study is to explore the role of digitalization in the agricultural sector in Colombia – focusing on the rice production – and to suggest best practices for the implementation of digital agricultural technologies and sustainable agricultural practices to achieve a reduction of food loss in the country and reach a sustainable production. The findings are provided by a collection of primary and secondary data, used in a comparative case study analysis between Colombia and Kenya, followed by in-depth expert interviews from Colombia. The experts provided information about the problems of food loss in the rice sector, as well as the current status of implementation of sustainable agricultural practices and digital agricultural technologies. In addition, an assessment of the recommendations based on the Kenyan case is presented to the Colombian experts. These recommendations are emphasizing how to address the main environmental, social and economic problems that are key to improving production in the rice sector. Overall the empirical evidence allows for additional recommendations considering the level of environmental emergency, as well as the level of knowledge and investment required by farmers to reduce food loss in the agricultural sector in Colombia. Focusing on reducing food loss to improve practices in the agricultural sector equips the various stakeholders (e.g., unions, farmers, policy makers, service providers) with tools to prioritize the needs of the sector through training, knowledge transfer and appropriate subsidies.

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LIST OF ABBREVIATIONS

ADB – African Development Bank

AfDB – African Development Bank Group

AGRA – Alliance for a Green Revolution in Africa

AGROSAVIA – Corporación Colombiana de Investigación Agropecuaria (Colombian Corporation for Agricultural Research)

AHP – Analytical Hierarchy Process

AI – Artificial Intelligence

AMTEC – Adopción Masiva de Tecnología (Massive Technology Adoption Programme (AMTEC)

APHLIS – African Postharvest Loss Information System

ARC – African Rice Center

ASAL – Arid and semi-arid areas

ASTGS – Agricultural Sector Transformation and Growth Strategy

AWD – Alternative Wetting and Drying

CARD – Coalition for Africa Rice Development

CCAFS – Climate Change, Agriculture and Food Security

CFA – Connected Farmers Alliance

CGIAR – Research Program on Climate Change, Agriculture and Food Security

CICO – Consumer Research Center

CIAT - International Center for Tropical Agriculture

CSA – Climate-Smart Agriculture

DANE – Departamento Administrativo Nacional de Estadística (National Administrative Department of Statistics)

DPN – Departamento Nacional de Planeación (National Planning Department)

DSM – Digital Soil Mapping

ERP – Enterprise Resource Planning

FAO – Food and Agriculture Organization of the United Nations

FEDEARROZ – Federación Nacional de Arroceros (National Federation of Rice Producers)

FENALCO – Federación Nacional de Comerciantes (National Federation of Merchants)

FEWS NET – Famine Early Warning System Network

FLI – Food Loss Index

FLW – Food loss and waste

FNA – National Rice Fund

FWI – Food Waste Index

GDP – Gross domestic product

GHG – Greenhouse gases

GIS – Geographic Information System

GNSS – Global Navigation Satellite System

GPS – Global Positioning System

HELP – High Level Panel of Experts

HYV – High-Yielding Varieties

ICBF – Instituto Colombiano de Bienestar Familiar (Colombian Family Welfare Institute)

ICIPE – International Center for Insect Physiology and Ecology

ICT – Information and Communication Technologies

IDEAM – Instituto de Hidrología, Meteorología y Estudios Ambientales (Institute of Hydrology, Meteorology and Environmental Studies)

IFAD – International Fund for Agricultural Development

IFPRI – International Food Policy Research Institute

IoT – Internet of Things

IPCC – Intergovernmental Panel on Climate Change

IPM – Integrated Pest Management

IRRI – International Rice Research Institute

JICA – Japan International Cooperation Agency

KALRO – Kenya Agricultural and Livestock Research Organization.

KAOP – Kenya Agricultural Advisory Platform

LBDA – Lake Basin Development Authority

MADR – Ministerio de Agricultura y Desarrollo Rural (Ministry of Agriculture and Rural Development)

MADS – Ministerio de Ambiente y Desarrollo Sostenible (Ministry of Environment and Sustainable Development)

MCE – Multi-Criteria Evaluation

MDG – Millennium Development Goals

MIRI – Multiple Inlet Rice Irrigation

NDVI – Normalized Vegetation Index

NERICA – New Rice for Africa

NGO – Non-Governmental Organization

NIB – National Irrigation Board

NPO – Non-Profit Organization

NRSD – National Rice Development Strategy

OECD – Organisation for Economic Co-operation and Development

RTK – Real Time Kinematic

SDG – Sustainable Development Goals

SIPRA: Sistema de Información para la Planificación Rural Agropecuaria (Rural Agricultural Planning Information System)

SPAD – Soil Plant Analysis Development

SRI – System of Rice Intensification

STRASA – Stress Tolerant Rice for Africa and South Asia

TDR – Time Domain Reflectometry

UPRA – Unidad de Planificación Rural Agropecuaria (Rural Agricultural Planning Unit)

WCED – World Commission on Environment and Development

WEF – World Economic Forum

WKRRDP – Western Kenya Rainfed Rice Development Project

1 INTRODUCTION

The development of agriculture has had a revolutionary impact on the lifestyle of humankind. Humanity moved from nomadic to permanent settlements 12,000 years ago, which has increased the amount of food available and generated an increase in population growth (Campos et al., 2018). Globalization has then opened up the possibility of making international products available to many countries through a global food supply chain. Although it is possible to find food from almost any country in a local store, this entails transporting products over long distances to create availability of products – which are seasonal and country-specific – all year around and for everyone, which has triggered several environmental problems, including the leakage of nutrients needed from food (Velasco-Muñoz et al., 2021), the creation of food loss and waste (FLW) [FAO, 2019], the increase in natural resources used (Aznar-Sánchez et al., 2020b; Hamam et al., 2021), the pollution of soil and water (Aznar-Sánchez et al., 2020b; Velasco-Muñoz et al., 2021), the loss of biodiversity (Aznar-Sánchez et al., 2020b), and the increase in greenhouse gas (GHG) emissions (Aznar-Sánchez et al., 2020b) due to the long journeys of food to reach its final destination.

According to an estimate by the Food and Agriculture Organization of the United Nations (FAO), population growth will reach 10 billion by 2050 (FAO, 2019; FAO 2018), which means that agricultural production will have to increase by 70 percent to meet global demand (FAO, 2019; Aznar-Sánchez et al., 2020a; Velasco-Muñoz et al., 2021). This is because agricultural processes are not efficient enough due to the misuse of agrochemicals such as fertilizers and pesticides (Aznar-Sánchez et al., 2019), lack of knowledge of farming techniques (FAO, 2019), inefficient infrastructure (Dora et al., 2021; Hamam et al., 2021), overproduction due to limited information (Dora et al., 2021) and external climatic conditions (FAO, 2019; Dora et al., 2021; Hamam et al., 2021). Moreover, current agricultural activities already have negative consequences such as environmental pollution and degradation of the natural resources that are the basis of food production. Adding that almost 30 percent of the food produced in the world is lost or wasted (Gustavsson et al., 2011; Principato et al., 2019). Thus, the increase of food demand will drive changes in agricultural production, increasing pressure on natural resources and intensification levels (Aznar-Sánchez et al., 2020b), causing deforestation due to the expansion of agriculture to natural ecosystems (Aznar-Sánchez et al., 2019).

To achieve sustainable agricultural production, it is not only necessary to increase agricultural productivity, but also to reduce food loss along the supply chain. Food loss has an economic impact on the growth of smallholder farmers, as it affects their income and productivity (Fan, 2017). It also reduces the availability of local and global food, which negatively affects health (FAO, 2014). At the same time, soil is deteriorated, water and energy are wasted, and GHGs are emitted, i.e., resources are depleted in food that does not reach the final consumer (FAO, 2011; Kummu et al., 2012; Lipinski et al. 2013). This increases malnutrition and production costs, reduces food security and efficiency of the food system, generates waste and pollutes the planet (FAO, 2019).

Digital technologies could play a key role in the development of sustainable practices in the agricultural sector, because they offer opportunities to boost crop yields, lower food losses, and improve the effectiveness of supply chains (FAO & ITU, 2019). According to FAO (2019), there are five types of digital technologies that can be implemented in the sector a) mobile devices (mobile applications, social media and online platforms); b) remote sensing technologies (Internet of Things (IoT), drones and satellite imagery); c) Big Data (cloud computing and data science); d) integration and coordination systems (blockchain, Enterprise Resource Planning (ERP), financing and insurance systems); and e) intelligent systems (Deep Learning, Machine Learning, Artificial Intelligence (AI), robotics and autonomous systems) [Trendov et al. , 2019, p. 3]. As reported by the OECD (2018), the main technological tools aimed at the agricultural sector are: platforms, sensors, IoT, robots, drones, Big Data, cloud computing, AI and Blockchain (Sotomayor et al., 2021, p. 18).

Colombia is one of few countries with great potential to expand its agricultural area without affecting the area of natural forests, due to its land availability, water resources and climatic diversity (FAO, 2018b) and could thereby play a crucial role in moving towards a sustainable agricultural production globally. However, the agricultural sector is one of the least productive in the country and lags behind in the implementation of technologies (Sotomayor et el., 2021). Finding best practices that can be implemented in the sector to increase productivity without harming the environment is fundamental in adapting the Colombian agricultural sector into a major contributor to sustainable agricultural production at the global level.

Rice is a staple food for more than half of the world's population (Lantin, 1999; FAO, 2002; Childs, 2022), considering strongly related to food and nutrition security in developing countries (Muthayya et al., 2014), as well as primary source of jobs and income (Lantin, 1999). In Colombia, rice is the third most important crop, behind coffee and maize, where up to 2 million people are employed along the value chain (Lacambra et al., 2020). In 2020, the harvested area was 596,415.00 ha with a production of 3,424,119 tons (FAO, 2022a). According to rice sector experts, the sector could grow by 60 percent over current levels, but support is needed to reduce production costs, set better financial instruments with long-term scope, and improve agricultural practices due to its dependence on water, the need for adequate temperatures, and its vulnerability to climatic events and other weather hazards (Lacambra et al., 2020).

1.1 Research aims and objectives

The purpose of this thesis is to better understand the role of digitalization in the agricultural sector in Colombia – focusing on the rice production – and to suggest best practices for the implementation of digital agricultural technologies and environmentally friendly practices to achieve a reduction of food loss in the country and reach sustainable agricultural production. The research question to be answered is:

What types of digital technologies are best suited to support the agricultural sector in Colombia on the way towards sustainable practices with the aim of reducing food loss?

The research goal is to identify the potential role of digital technologies in making agriculture more sustainable, especially on-farm activities, i.e. during pre-harvest, harvest, and post-harvest levels that can be integrated in the rice production in Colombia to reduce food loss. This takes advantage of the country's potential to expand its agricultural area, without abusing natural resources, while maintaining or reducing GHG emissions. As stated by FAO (2019), to conduct a food loss research is required to understand where in the agricultural process food loss occurs, in which products, and what environmental footprints are affected to be able to generate a local analysis. In addition to best practice recommendations, it is important to understand how to implement any digital technology and the potential benefits and risks involved.

1.2 Structure of the thesis

The structure of the study has the following order. Section 2 includes a literature review with definitions of the key concepts used in the analysis to give an overview of the thesis research. It includes the agricultural sector with its impacts on the environment and the relation to food loss, as well as sustainable agricultural practices and digital agricultural technologies. It should be noted that most of the definitions related to food loss are based on reports made by the Food and Agriculture Organization of the United Nations (FAO). Due to the lack of a common global definition and to obtain uniformity in the thesis. Section 3 describes the methodology applied and how the data was collected. Section 4 explains the case study, a comparison made between the rice sector in Colombia and Kenya. Section 5 shows the experts interview for validation of the Colombian case, highlighting the findings. Section 6 presents the results obtained from the analysis and the conclusions, and main limitations and opportunities for future research are provided.

1.3 Conceptual framework

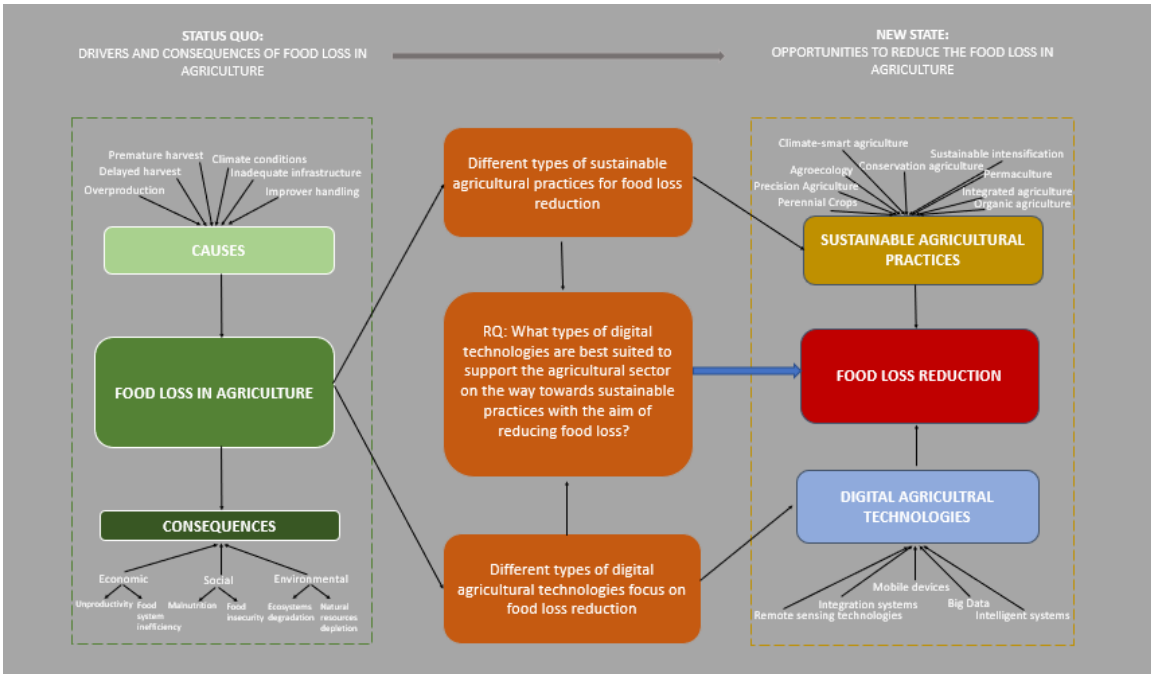

FIGURE 1: CONCEPTUAL FRAMEWORK

Source: own work

The conceptual framework is used to provide the theories and guiding concepts relevant to answering the research question, showing the importance of the relationship between variables and how they can provide insights into the research topic. Although the conceptual framework has different definitions according to different authors, as a commonality the term is used to refer to a specific function and a set of connections within the research process (Leshem & Trafford, 2007). For this study, two definitions are chosen, one by Miles and Huberman (1984, p. 33) who explain a conceptual framework as "the current version of the researcher's map of the territory being investigated"; and Weaver Hart's (1988, p. 11) who describes the concept as "a structure for organizing and supporting ideas; a mechanism for systematically arranging abstractions; sometimes revolutionary or original, and usually rigid".

In the agricultural sector there is a status quo in which production is neither sustainable nor efficient, due to different elements that cause food loss, such as limited physical infrastructure, lack of training, lack of access to information, overproduction, premature or delayed harvesting and climatic conditions. This generates negative economic, social and environmental consequences. From the economic point of view, the possibility of growth of smallholder farmers is reduced, due to the reduction of income from food costs that do not reach the next step in the supply chain, decreasing productivity. On the social side, the availability of food for the final consumer decreases, reducing food security and increasing malnutrition, mainly in vulnerable groups. From the environmental point of view, resources are depleted due to the degradation of soil, water and energy used and GHGs emitted in products that do not reach the end consumer, generating waste and polluting the planet unnecessarily.

To obtain a new state of agriculture, it is vital not only to improve the efficiency of agricultural production, but also to reduce food loss along the supply chain. The latter is an aspect that has not been explored in depth. Therefore, the author looks for the most suitable digital agricultural technologies and sustainable agricultural practices to reduce food loss within the supply chain. Since the solutions are different depending on the geographical conditions, the type of product and the part of the food supply chain to be focused on, chosen a specific case is needed. In this study, the rice sector in Colombia is investigated in the production part, i.e., pre-harvest, harvest and post-harvest. The objective is to focus on the right elements - both environmentally friendly practices and digital technologies - to transition to sustainable practices in the agricultural sector in Colombia. For this, it is important to consider at what point a low, medium or high level of knowledge and investment is needed to generate such a transformation.

2 LITERATURE REVIEW

2.1 Agriculture

The agricultural sector is an economic activity that belongs to the primary sector, which can be defined as "the science, art, or practice of cultivating the soil, producing crops, and raising livestock and in varying degrees the preparation and marketing of the resulting products" (Merriam-Webster Dictionary, 2020 cited by Velasco-Muñoz et al., 2021, p. 1).

Agriculture has changed enormously throughout human history due to a series of revolutions that have brought efficiency and profitability to production. The first agricultural revolution (ca. 12,000 ago) known as Neolithic Agricultural Revolution allowed humankind to establish civilizations and societies generating exponential growth (Trendov et al., 2019). It was done by sowing plants and domesticating animals to multiply them and use their products, humans went from being predatory societies to cultivators and breeders (Campos et al., 2018).

Following this, the second Agricultural Revolution occurred between the mid-17th century and the end of the 19th century due to the adoption of mechanization and scientific principles to control problems such as the spread of animal diseases, uncontrolled breeding and overgrazing of livestock arising from the way of production (Campos et al., 2018). These actions increased productivity and efficiency. However, in 1798 Thomas Malthus predicted in his *An Essay on the Principle of Population* that the world's population will grow at a higher rate than the food production that will be obtained from it, so that there will not be enough food to supply it, leading to famine and mortality (Herder et al., 2010).

Contrary to predictions, since the end of World War II, agriculture production was maximized along with the reduction of food prices by the introduction of technologies, the intensive use of pesticides and chemical fertilizers (Brodt et al., 2011; FAO, 2018c) and the availability of fossil fuels as a cheap and unlimited energy source (Gomiero et al., 2011). By the second half of the 20th century, the majority of industrialized nations had eliminated the threat of starvation through persistent food surpluses, while the development of these innovations in developing countries was significantly slower (IFPRI, 2002).

The Green Revolution, therefore, occurred in 1960 with the development of more resistant crop varieties, the use of agrochemicals, mechanization in the field and technological innovations (Campos et al., 2018; Trendov et al., 2019), allowing food production to keep up with the increase in global population (Herder et al., 2010). It was a new model of agriculture based on specialized production processes that were incorporated into a transnationalized agroindustrial system (Barkin, 2001).

Furthermore, between 1970s and 1980s, biotechnology appeared with DNA cloning, implementing genetic modification technologies to plants (Meiri & Altman, 1997), producing higher yields and increasing productivity. This was achieved due to investment in agricultural research and the development of high-yielding varieties (HYV) by foundations in developed countries for production in developing countries (IFPRI, 2002; Gomiero et al., 2011). The crops that become dominant at that time were wheat and rice due to the control of crop genetics, the use of agrochemicals and irrigation (Tilman, 1999). Both considered the most important crops in developing countries. Due to the high yields of these two crops, both began to expand, taking land away from other crops (IFPRI, 2002), being the beginning of monoculture. The Green Revolution, therefore, led to increased land profitability, higher farmer incomes and lower commodity prices, as well as reduced poverty and increased nutrition in developing countries.

However, all these benefits have taken place at the expense of the environment, with consequences such as water pollution, soil depletion, air pollution, GHG emissions and threats to human health (Brodt et al., 2011), and at the same time, income inequality, unequal asset distribution and worsening absolute poverty emerge (IFPRI, 2002). In fact, following the intensification of agriculture in the Green Revolution, soil degradation became one of the major environmental challenges, with pesticide contamination, erosion, increased salinity, loss of organic matter and loss of biodiversity as the main negative effects (Campos et al., 2018).

Due to the negative environmental consequences of the green revolution, sustainable agriculture was introduced in 1980s as a critique of developed practices and as an alternative option to the current one. The model is based on the reduction of the use of non-renewable resources, the use of energy-efficient technologies, the reduction to minimum levels or non-use of agrochemicals, the implementation of less specialized farming through mixed crop-livestock systems (Campos et al., 2018; Robinson, 2009), as well as the integration of biological and ecological processes and the preservation of the natural resources base for agricultural production (Gomiero et al., 2011).

Although investment in research helped alleviate poverty and human nutrition, from the 1980s to the mid-2000s agricultural development aid in developing countries almost halved, and research also declined (Popkin, 2020). That was not a problem at the time, given from 1960 to 2015, agricultural production tripled due to the significant expansion of land use and natural resources, and there was also a boom in globalization and industrialization of food (FAO, 2018a). The main consequence was the expansion of supply chains, which generated an increase in the distance between the farm and the final food consumer. This leads, however, to increased pollution with more GHG emissions, as well as deterioration of soil, water and air quality and increased effects of climate change such as droughts and floods (Meiri & Altman, 1997).

In late 2007 and early 2008, world food prices rose sharply, with maize, wheat and rice being the commodities with the highest prices, leading to increased global attention to the food crisis (Mittal, 2009). The main causes were, on the one hand, the decline in agricultural production growth due to reduce investment in agriculture, such as in public aid and research; and on the other hand, the increase in production costs due to higher energy prices, biofuels competition for land and reduction in food stocks (Hovland, 2009; Mittal, 2009). Thus, the food crisis increased poverty and undernourished impacting most developing countries and low-income groups (Mittal, 2009; Nellemann et al., 2009).

While agriculture is still dependence on the availability of natural resources, the demand for food keep increased due to the population growth (Nellemann et al., 2009; Gomiero et al., 2011). According to the 2009 report *The Environmental Food Crisis,* there are two options for producing food needed to feed humanity, either a price increase effect and additional investment in agriculture to compensate for yield declines, or agricultural expansion at the cost of natural forests being converted to cropland and resulting in biodiversity loss (Nellemann et al., 2009).

The impact of climate change on agriculture has already had negative effects on yields as a result of the decrease in available water due to groundwater salinity, the reduction of arable land due to soil degradation, and the fact that fertilizers and pesticides have already reached their maximum yield levels (Herder et al., 2010). Therefore, the discussion of a new green revolution is opened, in which biotechnology, organic farming, and agroecology working together can increase yields and minimize the environmental impact of industrial agriculture through sustainable intensification, not without developing them with the inclusion of smallholder and family farmers, as they represent the majority of society suffering from poverty and malnutrition (Holt-Giménez, & Altier, 2012).

In 2017, the next phenomenon happened, it was the digital agriculture in which the first fully automated crop was harvested (OECD, 2017), which offered new opportunities for agriculture thanks to the interconnected world and information technologies (Lioutas et al., 2021). Digital technologies can optimize agricultural production systems and improve the monitoring and control of crises along the supply chain (Klerkx et al., 2019), as well as increase farmers' access to information and their technical efficiency (Schroeder et al., 2021). Nonetheless, to adopt digital technologies in agriculture, it is important to consider what are the technological packages that can be adopted by all sizes of farms, and what type of inputs are required to have the capacity to access and understand the information provided by external parties (IFPRI, 2002).

Since 1961, the amount of food available per person has increased by more than 30 percent due to the use of nitrogen fertilizers and water resources for irrigation (Mbow et al., 2019). Nevertheless, undernourishment has also been on the rise since 2014 with an estimated 821 million malnourished and with increasing poverty especially in rural areas (FAO, 2018a; Schroeder et al., 2021), while food production must increase by 50 percent to be able to feed humanity by 2050 (Mbow et a., 2019; Laurett et al., 2021). The current challenges facing agriculture are, on the one hand, an increase in demand for food due to continued population growth, and on the other hand, a reduction in crop yields due to the effects of climate change. The agricultural sector not only is affected by climate change, but also contribute to it (FAO, 2018a). Thus, a new green revolution is being discussed, not only as a solution to increase crop yields, but to make agricultural practices resilient to climate change and more environmentally friendly (Herder et al., 2010).

2.1.1 Agriculture classification systems

Agricultural systems can be classified in different ways and there is no a generic system that is fully comprehensive and suitable for all uses (Robinson et al., 2011). According to Kostrowicki (1977), agriculture can be categorized in fourth groups, the first group is based on social characteristics, focusing on who owns the land and what is the scale of the operation. The second group focuses on the operational characteristics, describes what the labor and capital inputs are and how the operation works. The third group emphases on production, i.e., how much is produced and for what purpose. The fourth group defines the structural characteristics, i.e., what are the enterprise's combinations in terms of land use and economic purpose (Kostrowicki, 1977).

As stated by Ruthenberg (1980), farms are categorized in accordance with management characteristics, with collection and cultivation being the classification for crops (Ruthenberg, 1971; Fresco & Westphal, 1988; Robinson et al., 2011). Collecting is the method of directly obtaining plant products, including regular or irregular harvesting. Cultivation are organized following different features such as type of rotation, intensity of the rotation, water supply, cropping patterns and animal activities, implements used for cultivation and degree of commercialization.

The Dixon et al. (2001) model provided a classification of farming systems in developing countries focused on two main aspects, the available natural resource base and the dominant pattern of farming activities and household livelihoods. Within these aspects, the categories were divided into whether agriculture was rainfed or irrigated, agroecology, and location (urban/coastal) [Robinson et al., 2011; Dixon et al., 2001]. Therefore, for the purpose of this thesis, the classification used is the degree of commercialization, i.e., subsistence agriculture, semi-commercial agriculture and commercial agriculture.

2.1.1.1 Subsistence agriculture

Subsistence agriculture is defined by Barnett et al. (1997) as ‘‘farming and associated activities which together form a livelihood strategy where the main output is consumed directly, where there are few if any purchased inputs and where only a minor proportion of output is marketed” (Morton, 2007, p. 19680), i.e. the production in a specific farm is focused on family food rather than for commercial sale. Farmers have a strong tendency to use less productive technologies and simpler techniques, have low income levels of living, limited amount of options, decision-making influenced by cultural and social factors, less external contacts in the food supply chain, and a very slow process of changing production practices (Wharton, 1969).

There are three types of techniques in subsistence agriculture. The first is intensive subsistence, which is the most widely practiced in the world (Dastrup et al., 2019). It is generated in humid and tropical regions and is characterized by the adaptation of the landscape to food production. In this case, a lot of labor is needed on a limited amount of land and the most commonly used crops are rice, wheat and barley. The second is itinerant agriculture, in which farmers move to new places every few years to cultivate other land that has not been cultivated before, because the fertility of the soil is exhausted. Another type of method that is implemented is slash and burn, the first clears space and the next fertilizes the soil, however, this practice contributes to deforestation, i.e., damage to the environment. The products that can be harvested in this case are corn and sugar cane. The last is pastoral nomadism focuses on domesticated animals and they live in arid regions because the climate is too dry to harvest crops. The type of animals chosen by nomads depends on the culture of the region, the prestige of the animals and the climate (Dastrup et al., 2019).

2.1.1.2 Semi-commercial agriculture

In semi-commercial agriculture, there is a surplus generated from the products used for subsistence family farming that is decided to sell. In this case, the farm is moderately specialized and includes both agricultural and non-agricultural products (Leavy & Poulton, 2008). Agricultural production is sensitive to market trends because, as economies grow, family farming is moving away from traditional self-sufficiency objectives and towards income and profit-oriented decision making (Pingali & Rosegrant, 1995).

2.1.1.3 Commercial agriculture

Commercial agriculture is the production of crops and the slaughter of animals for sale in the global marketplace. The food is not sold directly to the consumer, but to a food processing company where it is transformed into a product (Dastrup et al., 2019). The main difference between subsistence and commercial agriculture is that in commercial agriculture the amount of technology implemented is higher, labor is reduced, there is overproduction, and there is a limited variety of products. However, both practices lead to environmental impacts, such as water pollution, land degradation and biodiversity loss, as Hosonuma et al. (2012) point out "commercial agriculture is the most important driver of deforestation, followed by subsistence agriculture" (Hosonuma et al., 2012, p. 1).

2.1.2 Impacts of agriculture on the environment

Despite the fact that agriculture is an economic activity that works close to nature, it uses large amounts of natural resources, water and energy in an unsustainable way (Thyberg & Tonjes, 2016). Agriculture uses 38 percent of the world's land area, with one third for cropland and two thirds for grazing livestock (FAO, 2020), 70 percent of all freshwater withdrawals (World Bank, 2020) and 31 percent of human-caused GHG emissions (United Nations, 2021). It is estimated that agriculture accounts for about 80 percent of deforestation worldwide (FAO, 2017), which is a main source of GHG emissions. Producing food contributes to climate change, land-use change, depletion of freshwater and pollution of ecosystems resulting in biodiversity loss, eutrophication, ecological degradation and emissions of GHG (FAO/IWMI, 2018; Springmann et al., 2018; Thyberg & Tonjes, 2016).

In this sense, productive growth of agriculture come at a cost to the natural environment. Even with investments and technological innovations in agricultural production, land yields are lower, therefore, the reduction of food loss is necessary to improve productivity and reducing the need to increase production (FAO, 2017).

2.1.3 Food loss in the agricultural sector

Food is considered to be any processed, partially processed or unprocessed substance intended for human consumption that may be of animal or plant origin (FAO, 2019). Food loss is a global problem that generates economic, social and environmental consequences. One out of every four calories destined to feed humans does not reach its final destination (Lipinski, B. et al. 2013), with 3.1 billion of people worldwide lacking access to healthy food and 828 million going hungry (FAO, IFAD, UNICEF, WFP and WHO, 2022).

As a consequence, a greater use of resources such as land, water and energy has been used to produce additional food to compensate for this loss but emitting more GHG (FAO, 2011; Lipinski, B. et al. 2013). According to FAO data from 2011 and 2013, food loss and waste (FLW) are responsible for the consumption of 250 km^3 of water, corresponding 6 percent of total water withdrawals, the use of approximately 1.4 billion hectares of land, being approximately 30 percent of the agricultural land in the world, and 3.3 giga tons of carbon dioxide emissions, representing 7 percent of total GHG emissions (FAO, 2013; FAO, 2019; Nicastro & Carillo, 2021).

Food loss and food waste are two important issues in the agricultural sector because they are related to productivity, food system efficiency, food security and nutrition, and environmental sustainability (FAO, 2019; FAO, 2022c). Although it is impossible to completely eliminate food loss and waste, it can be reduced to levels that increase producer and consumer incomes, improve global food security, and decrease resource use and GHG emissions. The two concepts of food loss and food waste are often confused with each other because they lack a common global definition and standard methods (Okawa, 2015; FAO, 2019). Thus, it makes it difficult to conduct comparative studies between different countries and organizations and also to assess interventions to reduce them. According to the FAO (2019) the main issues are: what is considered food, what part of the supply chain is considered, the differences between food loss and food waste, and the consideration of the loss in quantitative and/or qualitative terms.

To understand the differences between food loss and food waste, it is necessary to clarify the definitions, which were taken from the concepts developed by the Food and Agriculture Organization of the United Nations (FAO)). FLW are considered the decrease in the quantity or quality of food along the food supply chain referring to the edible parts of plants and animals harvested and produced (FAO, 2019; Okawa, 2015). Quantitative loss is related to physical FLW, i.e., decrease in mass, while qualitative loss refers to loss of value, which can be nutritional or economic. Food loss occurs from harvest/slaughter/catch up to, but not including, the retail level; while food waste occurs at the retail and consumption level (FAO, 2019). Food redirected to other economic purposes (e.g., to feed animals, as seeds, and industrial processes) and inedible parts are excluded (FAO, 2019).

2.1.3.1 Measurement of food loss

Both concepts food loss and food waste are commonly measured in physical terms (tons), but they can also be issued in volume, caloric, nutritional content, and economic value (FAO, 2019).

Although there has not been enough research in the field of food loss, i.e. there are no exact numbers on the amount of it in the world to be able to measure its reduction. There are some reports done by FAO in 2011, 2013 and 2019 with information on certain countries that have data available and with additional assumptions and averages implementation to generate a global conceptual framework. The aim is to harmonize and systematize data to facilitate the research of FLW and improve data collection.

The amount of food lost and wasted worldwide is 1.3 billion tons per year, which is equivalent to 33 percent of the entire world food supply chain (Meybeck et al., 2011), being responsible of the 8 percent of annual GHG (Hanson & Mitchell, 2017), consuming one-quarter of all water used by agriculture (Kummu et al., 2012; Hanson & Mitchell, 2017) and generating approximately $940 billion in economic losses globally (FAO, 2015; Hanson & Mitchell, 2017). The highest lost in weight are perceived in roots, tubers and oil-bearing crops followed by fruits and vegetables (FAO, 2019).

In 2015, the 2030 Agenda for Sustainable Development Goals (SDGs) was adopted, including its 17 goals (United Nations, 2015). SDG number 12 (responsible consumption and production) gives special attention to reducing food loss and waste, precisely in target 12.3 which states "By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses" (FAO, 2016).

Although the measurement of FLW has not been easy, two separate indicators have been created to assess indicator 12.3.1. The first is the Food Loss Index (FLI) by the FAO and the second is the Food Waste Index (FWI) by the United Nations Environment Programme (UN Environment). According to FAO (2019), to measure food loss, food products can be divided into 5 commodities groups: cereals and pulses; fruits and vegetables; roots, tubers and oil-bearing crops; animal products; and fish and fish products. The FLI assess the global food loss from post-harvest to, but excluding, retail focusses on 10 key commodities by country and ranked by productive value (FAO, 2019). The value is 13.8 percent in 2016 and 14 in 2019, as for FWI, the first estimate was in 2019 with 17 percent, being 931 million tons of food waste (Nicastro & Carillo, 2021).

According to Nicastro & Castillo (2021), 24 percent of FLW is at the production stage, 24 percent at the post-harvest stage and 35 percent at the consumption stage, accounting for more than 80 percent of global FLW (Nicastro & Carillo, 2021). Developing countries generate more losses than waste and these are mainly located at the production stage (30 – 40 percent), specifically 14 percent at harvest and 15 percent at post-harvest, due to technical, financial and management constraints, as well as inefficient storage and refrigeration tools; while developed countries produce more waste than losses and are located at the consumption stage (40 – 50 percent) due to poor purchasing habits in society (Meybeck et al., 2011; Dora et al., 2021; Nicastro & Carillo, 2021).

2.1.3.2 Causes of food loss

The causes of food loss vary among countries and products, since they depend on geographical, socio-economic and cultural context (FAO, 2019). Although in general terms, some triggers are crop yields and production techniques, inadequate harvesting time, climate conditions, lack of good infrastructure and capacity, deficient storage conditions, inefficient distribution system and grading for quality or safety standards (Meybeck et al., 2011). The main causes of food loss are explained through the decisions made by farmers and the type of losses they produce.

Decisions and external factors	*Why food loss occurs?*
Overproduction	• Poor demand forecasting that generates that products remain unharvested in the field because they are no longer profitable for the season (Dona et al., 2021). • Under- and over-sized products that cannot be sold (cosmetic defects). (Dona et al., 2021) • To prevent damaged due to unpredictable weather events (Nicastro & Carillo, 2021).
Premature harvest	• Food shortages • Urgent need for cash • Fear of theft • The result is that food products lose nutritional value and even become unfit for consumption (HLPE, 2014; Nicastro & Carillo, 2021).
Delayed harvest	• Potential attacks by biotic factors such as pests, rodents and fungi because products that reach maturity are left in the field (Nicastro & Carillo, 2021).

Climate conditions	• Abiotic factors such as high temperatures can affect crops in the proper formation of flowers and fruits (Nicastro & Carillo, 2021) • Colder weather can increase the likelihood of insect and fungal diseases (Nicastro & Carillo, 2021).
Inefficient cooling system and inappropriate storage	• Losses caused by the appearance of molds, insects, rodents and other pests (Abass et al., 2014; Dona et al., 2021).
Improver handling	• Out-dated techniques, lack of adequate knowledge of handling and lack of quality equipment lead to technical inefficiency. (Dona et al., 2021). • Damage to food products facilitating the entry of pathogens (Nicastro & Carillo, 2021).

TABLE 1: CAUSES OF FOOD LOSS

Source: own work

2.1.3.3 Impacts of food loss

The impact of food loss can be seen in three aspects: economics, nutrition and food security, and environment sustainability (FAO, 2019). On the economic side, food losses impact the income growth and prosperity of smallholder farmers (Fan, 2017; Dora et al., 2021), so reducing food loss can increase productivity and improve the economic situation of society as a whole. In nutrition and food security, food loss at the quantitative and qualitative level means nutrient loss that contributes to micronutrient deficiencies and malnutrition (FAO, 2019). Therefore, reducing food loss can improve the availability and access to food, although it also depends on how close the stages of the supply chain are and how easy it is to access them. In terms of environmental sustainability, the amount of land, water and energy resources used must increase to meet global demand due to population growth, however, by reducing food loss it is possible to use the same inputs and produce more.

The impact of a product on the environment can be measured by its carbon footprint, its land footprint and its water footprint. Carbon footprint assesses the total amount of GHG emitted during the entire food life cycle (FAO, 2019), and is mainly used at the consumption stage. The other two are used at the primary production stage. Land footprint is the area required to produce a given food, where 56 percent of the total cropland area is used for food production, while 17 percent is used for losses and 20 percent for animal feed (Kummu et al., 2012). The largest crop land losses are for cereals at 45 percent, followed by oilseeds and pulses at 30 percent and fruits and vegetables at 19 percent (Kummu et al., 2012).

Water footprint is the amount of freshwater required to produce a food, 70 percent of global freshwater withdrawals are caused by the agricultural sector (Döll, 2009; Shiklomanov, 2000; Kummu et al., 2012), where 62 percent of irrigation water is used for food production, 20 percent is used for supply chain losses, 14 percent for animal feed and 5 percent for seeds and other uses. In the world, one of the highest water losses is in Latin America at 34 percent, where fruits and vegetables losses are high (Kummu et al., 2012).

2.1.4 Crops

Crops refer to plants that are harvested and used as food for humans, to feed animals, as seeds, and for industrial or other uses. According to agricultural classification, for human alimentation are food crops, such as staple crops (e.g., wheat), cereal and grain crops (e.g., maize and rice), legume crops (e.g., peas), root and tuber crops (e.g., potatoes), fruit crops (e.g., bananas), vegetable crops (e.g., spinach), oilseed crops (e.g., sunflower), sugar and sweetener crops (e.g., sugar cane), and beverage crops (e.g., coffee) [Balasubramanian, 2014]. For animal feed, these are referred to as pasture and forage crops, which are plants grown to feed grazing animals. For industrial and other purposes are non-food crops, such as rubber, latex and gum crops, tannin crops, fiber crops and biofuel crops (FAO, 2010; Balasubramanian, 2014).

Cereal crops are grasses that produce single-seeded fruits, considered a source of nutrients and energy for humans (Evers & Millar, 2002). It has been considered the main component of the human diet and is cultivated in large quantities throughout the world (Papageorgiou & Skendi, 2018). The crops included in the cereals group are barley, maize, millets, oats, rice, rye, sorghum and wheat (FAO, 2010). As for processing methods, there are dry milling (wheat and rye), malting (barley, maize, and wheat), pearling (rice, oats, and barley) and wet milling (maize and wheat) [Papageorgiou & Skendi, 2018].

2.1.5 Rice production

The term "rice" refers to all plant species of the genus Oryza of the family Poaceae (Gramineae) [Dagallier et al., 2021]. With more than 110,000 varieties of rice reported, only two are cultivated species, Oryza sativa - cultivated worldwide – and Oryza glaberrima - cultivated in West and Central Africa (Fukagawa & Ziska, 2019; Dagallier et al., 2021). Oryza sativa, however, is the most popular and extensively grown (Fukagawa & Ziska, 2019), being further classified into two subspecies, indica – long grain – and japonica – short grain (Dagallier et al., 2021).

The crop is a semi-aquatic annual grass plant that is grown in more than 100 countries and provides more than 20 percent of the global calorie intake (Muthayya et al., 2014; Fukagawa & Ziska, 2019). In the tropics, however, rice can be grown all year long, with two or three crops each year, when irrigation water is available (Dagallier et al., 2021). The physical conditions of growing the crop are specific, high average daytime temperatures, cooler nights during the growing season, an abundant water supply, a smooth soil surface that facilitates uniform flooding and drainage, and a hard subsoil that inhibits percolation (Chlids, 2022). There are four cropping systems for water supplementation: irrigated lowland, rainfed lowland, rainfed upland and deep water. The most widely used is the first, with 54% of the overall rice crop, followed by the second, with 25%, and the other two, with 13% and 8%, respectively (Dagallier et al., 2021).

The production process, i.e., pre-harvest, harvest and post-harvest operations, determine the quantity and the quality of the final rice production. In pre-harvest, the choice of the variety to be planted, making a crop schedule and getting the field ready for planting are important aspects because they influence production efficiency, the technology required for harvesting and threshing, and the agro-inputs used (Lantin, 1999).

Harvesting refers to all the activities that take place in the field, such as cutting the rice stalk or mowing the panicles, placing the rice on the stalk or stacking it for drying (Lantin, 1999). Direct seeding and transplanting are the two methods of seedling establishment, and the choice of method is based on different conditions, such as the degree of field flatness, the presence of irrigation systems and the availability of machinery (Dagallier et al., 2021). The process also involves water management, fertilizers application, and weed, disease and pest control.

Post-harvest operations are threshing, which consists of separating paddy grain from the panicle, and is done manually, mechanically, or with a treadle thresher, and cleaning the undesirable material from the grain (IRRI, 2012). The last step is drying, in which the moisture content of the grain is reduced for storage. The traditional method is sun drying, which is the cheapest method and is used in most developing countries (Lantin, 1999), and mechanical dryers which are used to eliminate water from wet drains (IRRI, 2012).

Paddy rice contains an outer layer of husk, layers of germ and bran, and the endosperm, which is the end product of harvesting and threshing rice grains (Muthayya et al., 2014), while milled rice is the result of removing or separating the husk and bran to create the consumable endosperm (Lantin, 1999). Rice can be also categorized as brown or white rice. Brown rice is produced by removing the husk from the grain, while white rice is produced by removing the bran layers and the germ, leaving just the endosperm (Dagallier et al., 2021). Although white rice is more consumed, brown rice is said to be healthier due to its bioactive components and minerals and vitamins that white rice lacks (Fukagawa & Ziska, 2019).

In 2021, there was a global production of milled rice of around 510 million metric tons (Shahbandeh, 2022). Thus, it is considered a staple food for more than half of the world's population (Lantin, 1999; FAO, 2002; Childs, 2022), being Asia, Sub-Sahara Africa and South America the regions with more consumption (Childs, 2022). For the majority of people living in rural areas of developing countries, rice cultivation operations are the primary source of job and income (Lantin, 1999). Although people that subsist on rice are particularly susceptible to vitamin and mineral deficiencies (VMD) [Muthayya et al., 2014].

Throughout the rice production, both quantitative and qualitative losses can occur, the main factors according to Lantin (1999) are excessive grain moisture content, inmature grains, high temperatures and insects that cause a reduction in the weight and volume of bulk grain and also contaminate them. This can occur due to inadequate processes in rice production. Harvesting and threshing are major challenges in field operations, and drying in post-harvest operations, which can be affected by aspects such as weather conditions, rice variety and technology used.

Moreover, rice production has negative consequences for the environment. The crop contributes to the increase in the concentration of GHGs in the atmosphere, producing mainly methane (CH_4), nitrous oxide (N_2O) and in lesser proportion carbon dioxide (CO_2) [Gupta et al., 2021]. CH_4 production is derived from the decomposition of organic materials in anoxic rice crops (Hussain et al., 2014), while N_2O is produced in the soil through microbial mechanism of nitrification and denitrification; it usually increases when available nitrogen (N) exceeds plant demand under wet conditions (Gupta et al., 2021; Hussain et al., 2014). Additionally, the use of inorganic fertilizer to increase rice production may raise the emissions of both. CO_2 emission depends on factors such as environmental conditions, soil procedures and organic matter added to the soil (Gupta et al., 2021), being the main sources of emissions residue burning, urea fertilization, tillage and respiration (Hussain et al., 2014).

On the other hand, rice cultivation is considered to be one of the most water-intensive crops, in which irrigation is one the activities with most water consumption. In an irrigated lowland production system, 1 kilogram of rice typically requires 1,432 litters of water (IRRI, 2012). This generates a serious threat to water availability as it is a staple food for a large part of the world's population and has been grown rapidly, accelerating the water scarcity around the world. Additionally, water management is one of the most important variables regulating GHG emissions during rice production (Hussain et al., 2014). Therefore, rice production has several challenges, not only finding land for the crop cultivation with water availability, but also making the production more efficient, minimizing water use and reducing GHG (Nikolaisen et al., 2021).

2.2 Sustainable agriculture

The term sustainable development came into use at the United Nations Conference on the Human Environment, held in Stockholm, Sweden, in 1972. It was the main conference on the environmental issue where the foundations for the protection and improvement of the human environment were outlined, together with suggestions for global environmental action (United Nations, 1973). Subsequently, the term had its own definition created by the World Commission on Environment and Development (WECD) in 1987, defining it as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987, p. 37). Sustainable development is a complex concept that combines three pillars: environment, economy and society, and focuses on finding a right balance among them (Meadowcroft, 2007).

Twenty years later, in 1992, another milestone was the Earth Summit in Rio de Janeiro, Brazil, where economic development, solutions to curb global pollution, the protection of natural resources and the promotion of the sustainable use of natural resources were discussed (Aznar-Sánchez et al., 2019; Aznar-Sánchez et al., 2020a; United Nations, 2022). In addition, there was a particular focus on the importance of introducing appropriate production models for agriculture, with a focus on making it less disruptive to ecosystems and less dependent on non-renewable energy sources (Barkin, 2001).

Afterward, the Kyoto Protocol was adopted in 1997 and entered into force in 2005, committing the world's nations to reduce greenhouse gas emissions (Aznar-Sánchez et al., 2019; Aznar-Sánchez et al., 2020a). In 2000, the Millennium Summit established eight Millennium Development Goals (MDGs) to set guidelines for improving livelihoods and the environment globally (United Nations, 2022). Followed in 2012 by the United Nations Conference on Sustainable Development in Rio, Brazil, also known as Rio+20, where the United Nations Environment Assembly was created, which became the global high-level decision-making body on the environment

(United Nations, 2022). Three years later, the United Nations Summit on Sustainable Development took place to adopt the 2030 Agenda for Sustainable Development, with 17 SDGs and 169 targets to build on the MDGs and complete what was not achieved. (United Nations, 2015).

One of the most crucial parts of sustainable development is the promotion of sustainability in agriculture. Sustainable agriculture must use natural resources, technology and natural fertilizers in the best possible way, while protecting the soil, minimizing the use of chemicals and avoiding damage to the environment (Laurett et al., 2021).

Sustainable agriculture can be defined in different ways. According to Doering (1992) "sustainable agriculture implies less specialised farming, requiring mixed systems of crops and livestock to reduce dependence upon purchased fertilisers" (Robinson, 2009, p. 1760). As defined by Parikh & James (2012, p. 8), it is "an approach to farming that focuses on production of food in a manner that can be maintained with minimal degradation of ecosystems and natural resources". It provides equal weight to the economic, social and environmental aspects in the agricultural area (Parikh & James, 2012). Moreover, as stated by Sarker (2017, p. 48) "sustainable agriculture is an integrated system of plant and animal production practices having a site-specific application that will maintain their productivity and usefulness to society by resource-conservation, socially viable, commercially competitive, and environmentally sound condition". As mentioned by Brodt et al., (2011), the goal of sustainable agriculture is to reduce the dependence on non-renewable energy sources bringing renewable sources options to the field, e.g. solar and wind power, or biofuel from waste.

However, there are some barriers to achieving sustainable agriculture that can be divided into macro-systemic, regulatory, administrative, financial and individual (Laurett et al., 2021). At the macro-systemic level, there are difficulties in keeping young people in rural areas and a lack of communication between consumers and farmers to understand wants and needs. At the regulatory level, there is a lack of government support for smallholder farmers and a lack of understanding of the legislation by farmers. In terms of administration, there is a lack of information and technical knowledge on the part of smallholder farmers to be more sustainable, as well as a lack of technical support and training from different institutions, both private and public. This makes it difficult to innovate and adopt new technologies, especially for smallholder farmers. Financially, there is a lack of financial resources, higher production costs and the requirement of large initial investments for more sustainable production. On the individual level, there is resistance to behavioural change and new ways of working, especially in traditional family farming.

By 2050 the world will have to feed an estimated of 10 billion of people, implying an expansion of agricultural production by approximately 70 percent (FAO, 2019; FAO, 2018; Aznar-Sánchez et al., 2020a; Velasco-Muñoz et al., 2021). The current question for the agricultural sector is whether the production system will be able to produce enough food to feed a world population that is growing exponentially over the years, while reducing impacts on the environment due to already scarce land and water resources, decreasing GHG emissions and mitigating the impacts of climate change.

The agricultural sector, therefore, must search for innovative systems that protect the natural resources, while increasing productivity, e.g. transformative processes such as agroecology, agroforestry, climate-smart agriculture, and conservation agriculture, which are based on indigenous and traditional knowledge (FAO, 2017).

2.2.1 Sustainable agricultural practices

2.2.1.1 Agroecology

Agroecology is a system that considers a crop field as an ecosystem and focuses on maintaining species diversity and ecological relationships in the field (Altieri, 1995). It is a holistic study that considers both human and environmental factors in agroecosystems, emphasizing the form, dynamics and function of their interactions (Gomiero et al., 2011). The discipline focuses on the complex dynamics of social-ecological processes, moving from reliance on chemical inputs to a holistic and integrated approach based on ecosystem management (FAO, 2017; Thompson et al., 2007). It is based on traditional farming systems that implement integrated land-use systems in which different types of crops are grown in different places and at different times to maintain fertility in the field and be less vulnerable to losses. It is a knowledge-intensive approach, founded on the capacity of local communities to produce and scale up innovations through farmer-to-farmer research (Holt-Giménez, & Altier, 2012; Thompson et al., 2007). The knowledge-intensive practices of agroecology are not only based on traditional farming systems, but also on the generation of new knowledge through participatory research with stakeholders (Mbow et al., 2019).

2.2.1.2 Conservation agriculture

Conservation Agriculture is defined by the FAO (2017) as a farming system that promotes the reduction of soil disturbance (i.e. minimizing mechanical tillage), maintenance of permanent soil cover, and appropriate crop rotation with diversification of plant species (i.e. at least three different crops) [FAO, 2017; FAO, 2013; Mbow et al., 2019]. The application of CA can bring immediate (e.g., reduced erosion, stabilized of crop yields and improved water productivity) and long-term benefits (e.g., increased soil organic matter content and improved soil structure); however, the effects of CA are site- and time-specific and cannot be generalized to all farming systems (e.g. Derpsch, 2003; Hobbs, 2007; Giller et al., 2009 cited by Kienzler et al., 2012). CA promote above- and below-ground resource conservation and maintain agricultural production under different climate change impacts by providing mitigation and adaptation benefits (Sapkota et al., 2015).

2.2.1.3 Permaculture

Permaculture is an agroecological movement defined by David Holmgren (2004, p. xix) as "consciously designed landscapes which mimic the patterns and relationships found in nature, while yielding an abundance of food, fibre and energy for provision of local needs" (Ferguson & Lovell, 2013, p. 252). Permaculture prioritizes the management design and integration of the elements in a particular landscape (Gomiero et al., 2011), focusing on the connections between the parts and how these can be changed to make the place function harmoniously (Whitefield, 1993). The objective of permaculture is to create a productive and integrated low-input culture of organisms that includes people, animals, plants and structures (Gomiero et al., 2011). It is a framework for integrating knowledge and different disciplines, hence, it is composed of both traditional agricultural practices and modern science and technologies (Ferguson & Lovell, 2013; Whitefield, 1993).

2.2.1.4 Organic agriculture

Organic agriculture is a resource conservation agricultural practice that can stabilize or increase agricultural productivity over the long term (FAO, 2018a). The objective is to generate crop productivity by preserving soil fertility, reducing soil erosion, and conserving water, biodiversity, and the ecological functionality of landscapes (Gomiero et al., 2011). According to the Codex Alimentarius Commission, “organic agriculture is a holistic production management system which promotes and enhances agroecosystem health, including biodiversity, biological cycles, and soil biological activity” (Codex Alimentarius, 1999, p. 2), while prohibiting the use of synthetic fertilizers, pesticides and genetically modified organisms (Gomiero et al., 2011). The agricultural methods use are crop rotation, natural management of pests, diversification of crops and livestock, symbiotic nitrogen fixation with legumes, and application of organic manure (FAO, 2018a), which generates a strong potential for building resilient food systems in the face of uncertainties (Scialabba & Müller-Lindenlauf, 2010).

2.2.1.5 Integrated agriculture

Integrated agriculture is a farming method that integrates conventional and organic farming practices (Gomiero et al., 2011), which requires a high level of knowledge regarding pest, weed and disease control (Vereijken, 1986). As part of the system, animal manure is used instead of chemical fertilizers and weeds can be controlled by cultivation practices and tillage (Gomiero et al., 2011; Vereijken, 1986). The integrated agriculture seeks not only economic yield, but also the minimum input of fertilizers, pesticides and machinery to avoid environmental pollution and to save non-renewable resources (Vereijken, 1986).

2.2.1.6 Sustainable intensification

To meet global demand and ensure food security due to population growth and the effects of climate change, there are two types of methods, extensification, i.e. using more land in agriculture; or intensification, increasing the productivity of existing agricultural land (Godfray and Garnett, 2014). Sustainable intensification focuses on increasing food production from existing cropland to have a lower environmental impact (Campbell et al., 2014), based on the idea that extensification generates more damage to the environment than its benefits. Land used to generate additional food could be land used for more sustainable practices (Godfray 2015 cited by Mbow et al., 2019). Sustainable intensification is defined by Vanlauwe et al. (2014) as the recognition that increasing agricultural productivity is related to the maintenance of other ecosystem services (Mbow et al., 2019).

As stated by FAO (2018a), only sustainable intensification of agriculture can reduce land demand and maintain soil quality (FAO, 2018a). However, to achieve sustainable intensification, four aspects need to be considered: food production needs to increase to meet global demand, most of the increase must come from existing agricultural land, it must be sustainable in all components of the food system, and different tools and methods must be considered in this process (Godfray & Garnett, 2014; Mbow et al., 2019). Similarly, it is important to bear in mind that any decision must consider the specific environmental context of each geographical location, e.g. the amount of land already degraded, the type of land available and the possible uses of that land, among others. In some cases, it is even better to reduce the production of one crop to increase the sustainability of the whole land.

2.2.1.7 Perennial Crops

Perennial crops emerged due to the negative consequences of soil tillage and the use of agro-chemicals on annual crops, affecting soil conservation and generating nitrogen losses (Gomiero et al., 2011). Perennial agriculture is used to minimize nutrient leaching, increase soil carbon se-questration, reduce soil erosion, increase temporary access to water, and provide continuous wildlife habitat (Batello et al., 2014; Zhang et al., 2011). Unlike annual crops, perennial crops are able to regrow after a normal harvest, maintain floret fertility, and produce grain (Batello et al., 2014), which also reduces management costs due to lower use of energy-intensive inputs, pesti-cides, and fertilizers (Gomiero et al., 2011).

Additionally, perennial crop species can generate greater ground cover, achieve longer growing seasons and a more extensive root system, which increases their competitiveness against weeds and is more effective in capturing nutrients and water (Zhang et al., 2011). The most significant advantage of perennial agriculture, therefore, is the preservation and growth of healthy soil eco-systems that can ensure long-term food security (Batello et al., 2014).

2.2.1.8 Precision Agriculture

Precision agriculture is an agricultural management system that optimizes field production by adjusting soil and crop management (e.g., regulating agrochemical application inputs, under-standing soil spatial variability, precise water management, and considering crop nutrient status) to meet the unique characteristics of each field (Gomiero et al., 2011; Hedley, 2014; Mbow et al., 2019). It has a technologically advanced approach that uses continuous monitoring of crop per-formance through the use of new technologies (e.g., using remote sensing, advanced software, geographic information systems (GIS), global positioning systems (GPS), and precision application equipment) [Gomiero et al., 2022; Hedley, 2014] with the goal of modifying inputs (e.g., fertilizer, irrigation, seed rate) to achieve cost efficiency and productivity and environmental gains (Hedley, 2015).

In addition, this farming system can also use low-tech by focusing on low capital-input farming, i.e., generating innovations through farmers' knowledge and experiences (Mbow et al., 2019). Precision agriculture then has the ability to provide better yields in a more efficient and sustain-able way compared to traditional low-precision methods improving food security, increasing eco-nomic returns and creating employment opportunities (Mbow et al., 2019; Hedley, 2014).

2.2.1.9 Transgenic Technology

Transgenic technology is defined as "a set of techniques used for transferring desirable gene(s) across taxonomic boundaries" (Gupta et al., 2013, p. 20). It is the fastest growing technology in agriculture, generating the technological advances needed to have the ability to control gene expression and perform gene transfers from one organism to another (Gomiero et al., 2011), being used to modify crops according to specific needs (Ahmad et al., 2012).

The advantages gained by crops through technological modifications are resistance to pests, improving water use efficiency, the ability to cope with drought or saline soils, the production of more nutrients, and the introduction of resistance to heavy metals and cold (Gomiero et al. 2011; Ahmad et al., 2012). The most common food plants that have used transgenic technology are tomato, rice, corn, soybean and wheat, among others (Ahmad et al., 2012; Gomiero et al., 2011). Transgenic technology has been considered an opportunity to meet global food demand while preserving the environment and decreasing agricultural environmental impact (Gomiero et al., 2011). However, there are environmental risks such as the likelihood of gene flow into nearby wild plants and the potential impact of gene flow on non-target organisms (Gomiero et al., 2011; Ahmad et al., 2012).

2.2.1.10 Climate-smart agriculture (CSA)

Climate-smart agriculture (CSA) is defined as “an approach for transforming and reorienting agricultural systems to support food security under the new realities of climate change” (Lipper et al., 2014, p. 1068). Its three objectives are improving productivity to be able to increase income, food security and development; enhancing resilience and adaptive capacity to climate change at multiple levels; and reducing GHG emissions and increase carbon sinks (Mbow et al., 2019; Campbell et al., 2014).

CSA emphasizes the implementation of flexible, context-specific solutions and also encourages coordinated actions with different stakeholders, e.g. farmers, the private sector, civil society, scientists, and policymakers to create solutions that make agriculture more resilient. Action is needed in four areas for effective implementation of CSA, building evidence and assessment tools, bolstering national and local institutions, creating coordinated and evidence-based policies, and improving funding and its effectiveness (Lipper et al., 2014). As Campbell et al. (2004) point out, CSA integrates climate change into sustainable agriculture planning and implementation and serves as a basis for priority setting.

2.3 Digitalization in the agricultural sector

The digitalization of agriculture emerged in the mid to late 20th century with the Green Revolution, being a period characterized by increased on-farm food production due to scientific advances adopted by developing countries (Lioutas et al., 2021). The 1990s saw an increase in the prevalence of mobile phones and the emergence of digital tools incorporated into mechanization, which enabled automatic steering of tractors, fertilizer spreaders and pesticide sprayers, as well as boosting the speed of information and knowledge transmission (Krishnan et al., 2020; FAO, 2022b).

Since the early 2000s, the combination of the digital and physical domains by collecting, transferring and managing data through information and communication technologies (ICT) has enabled the development of precision agricultural production systems (Krishnan et al., 2020). Similarly, disembodied devices, such as smartphones, are increasingly being used to provide information to producers through their sensors, high-resolution cameras and various applications (FAO, 2022b).

Since 2010, the ability of unmanned automation has been demonstrated to drive entire field patterns under autonomous management of tractor-implement functions, requiring less frequent operator intervention (Krishnan et al., 2020). The most advanced solutions are the implementation of IoT and AI with machine learning to collect, store and transfer data about the crop, field and machine status at the time of field operation, enabling monitoring and automation of crop care decisions, generating learning with agronomic data (Krishnan et al., 2020; FAO, 2022b).

As defined by the United Nations (2017), "digital agriculture is the use of new and advanced technologies, integrated into a system, to enable farmers and other stakeholders within the agricultural value chain to improve food production" (United Nations, 2017). It is a concept that emerged as a new alternative to provide solutions to the world's food problem while reducing its impact on the environment (Lioutas et al., 2021). The technologies are designed to improve food security, reduce waste and maintain economic income (Benyam et al., 2021).

The incentives of a farmer to adopt digital technologies are based on costs and benefits compared to the conventional farming methods (Schroeder et al., 2021). According to David’s (1975) model, there are three components to consider: the first is the objective of the farmers, i.e., to maximize profits, expected utility or minimize expected losses at a given point in time; the second is the heterogeneity in costs and benefits considering factors such as farm size, land quality, human capital, among others; and the last is the timing of adoption and the mix of components to be adopted, with farmers preferring to customize their adoption decisions to meet their needs (Schroeder et al., 2021).

There are also some barriers for farmers, especially smallholder farmers, when they want to adopt digital technologies. The first is related to digital skills to be able to understand and translate the information they receive from an app or platform (Krishnan et al., 2020), as there is low digital literacy in rural areas (FAO, 2022) and these processes involve high complexity (Krishnan et al., 2020). There is also a reluctance to change linked to older generations (FAO, 2022).

The second is the high cost of investment in these digital technologies (FAO, 2022; Krishnan et al., 2020), while there is a lack of available technologies suitable for smallholders (FAO, 2022). In addition, farmers prefer to rely on their social networks and local media to learn about agricultural technologies, but the costs of obtaining information are usually high, so there is little access to information on available agricultural technologies (Schroeder et al., 2021). In addition, there are external challenges, such as limited connectivity and availability of digital and physical infrastructure for digital technologies in rural areas (FAO, 2022). As stated by Kuijpers and Swinnen (2016), low levels of technology adoption and continued underdevelopment of agriculture are characteristic of low-income economies (Krishnan et al., 2020).

The benefits of adopting digital technologies can be seen in economic, social or environmental aspects, although with more benefits on the economic side. The value chain can be strengthened by minimizing information asymmetry and promoting knowledge sharing (Krishnan et al., 2020). At the same time, connection costs between sellers and buyers are reduced (World Bank Group, 2019), having the potential to reduce spatial and economic disparities in the agricultural sector (Schroeder et al., 2021) and reducing inequalities in accesing information, knowledge, technologies and generating markets crop stability (World Bank Group, 2019; Benyam et al., 2021).

In addition, farmers' decision making can be improved with accurate, site- and time-specific agronomic data (World Bank Group, 2019), helping farmers to spend less effort and time on management tasks, reducing the amount of agrochemical use (Lioutas et al., 2021), and improving the use of machinery and equipment (World Bank Group, 2019). Furthermore, yield production can be increased while improving product quality (Lioutas et al., 2021). With biotechnology, crop resilience can be improved and food traceability technologies can promote the minimization of food losses (Benyam et al., 2021).

From a social point of view, the adoption of digital technologies increases the need for relatively skilled workers (FAO, 2022), creating the opportunity to acquire skills and knowledge and formalize jobs, as well as increasing opportunities for youth and women entrepreneurs (Krishnan et al., 2020; World Bank Group, 2019). In addition, digital technologies generate better knowledge to build resilience to climate-related disasters by protecting local food systems and improving rural livelihoods and food availability (Benyam et al., 2021).

On the environmental side, farmers can reduce agricultural input application, waste and pollution from stormwater runoff by managing soil and water more sustainably with better access to information (Schroeder et al., 2021; Benyam et al., 2021). Simultaneously, GHG emissions, energy use, nitrous oxide emissions in soil and fuel consumption in machinery can be reduced (Schroeder et al., 2021). Overall, the environmental footprint of agriculture can be mitigated by implementing digital technologies (Lioutas et al., 2021).

However, the digitalization of agriculture has negative externalities. On the economic side, there is a risk of concentration of power by service providers who own the technology and access to data (World Bank Group, 2019; Lioutas et al., 2021), and there is an issue regarding data privacy and cybersecurity breaches (World Bank Group, 2019). Environmentally, there is also a potential risk in the increased farm specialization due to the introduction of digital technologies as they are adapted to specific crops, which may cause a reduction in biodiversity, soil and water degradation, loss of traditional crops and degradation of on-farm resources (Lioutas et al., 202; Schroeder et al., 2021). Digital technologies can also accelerate natural resource depletion as a rebound effect due to resource efficiency gains leading to increased use of machinery and energy and GHG emissions (Schroeder et al., 2021).

From a social point of view, one of the main problems is the low literacy of smallholder farmers, as some tasks become automated, which generate a potential loss of jobs (Schroeder et al., 2021; FAO, 2022; World Bank Group, 2019), mainly for people whose occupational alternatives are limited to those in agriculture, i.e. there is a limitation in the adaptation to the new conditions (Lioutas et al., 2021). Furthermore, infrastructure is a physical barrier that can increase inequalities and reduce inclusiveness (Lioutas et al., 2021), as the benefit of digital technologies depends on access to digital infrastructure and machinery (Schroeder et al., 2021). There are substantial differences in such infrastructure, between developing and developed countries, small and large-scale farms and remote and central areas among farmers, which may create territorial exclusion depending on their location (Lioutas et al., 2021). In addition, there is a risk that digitalization will reduce farmers' interest in their old knowledge, practices and networks, leading to disengagement from farming culture (Lioutas et al., 2021).

According to Lioutas et al. (2021), International Organizations (e.g. OECD, FAO and World Bank) considered the implementation of digital technologies in agriculture a possibility to improve the decision-making of farmers, while reducing agrochemicals use and increasing farm efficiency, however, non-governmental organizations (NGO)s, civil society and activists are more skeptical about the results, considering that negative consequences can arise. Hence, the digitalization of agriculture can regenerate food production and boost food security but can also be a threat to smallholder farmers viability due to the overconcentration of power by agro-tech companies.

2.3.1 Type of digital agricultural technologies

In this study, it is used the classification of digital agricultural technologies of FAO (2019) as mentioned before. The five groups are: a) mobile devices (mobile applications, social media and online platforms); b) remote sensing technologies (IoT, drones and satellite imagery); c) Big Data (cloud computing and data science); d) integration and coordination systems (blockchain, ERP, financing and insurance systems); and e) intelligent systems (Deep Learning, Machine Learning, AI, robotics and autonomous systems).

2.3.1.1 Mobile devices

Mobile devices are used in the development of agriculture through the integration of mobile applications, social media and online platforms. Mobile devices are considered the main source of access to the internet, where the use of social media has grown exponentially (Trendov et al., 2019). In the developing world, mobile communications technology has rapidly established itself as the most popular means of delivering voice, data and services (Qiang et al., 2012), which opens the door to the search for relevant applications to help farmers improve the practices in their fields.

There are many applications related to farming practices that provide means of communication and information transmission, offer transaction services and provide advisory services for decision-making. According to the study by Sekabina and Qaum (2017), mobile devices can improve the standard of living in rural areas because they improve access to information and markets while reducing transaction costs (Trendov et al., 2019).

The benefits of using mobile devices in the agricultural sector are the following: improved access to information, such as market data that reduces price distortions (Stephenson et al., 2021), weather and disease data that enables better disaster and risk management, and access to good agricultural practices that help improve yields (Qiang et al., 2012). Relationships between farmers and consumers are strengthened, reducing intermediaries in the value chain (Stephenson et al., 2021), and recording, accounting and traceability are improved, leading to increased efficiency and crop forecasting (Qiang et al., 2012; Trendov et al., 2019). There is improved access to finance, such as credit, insurance and payment methods that increase diversification of production and reduce losses (Trendov et al., 2019).

The main challenges for the use of mobile devices are the limited infrastructure in rural areas in terms of network, connectivity and electricity. Lack of training of staff to learn how to use apps, social media and online platforms correctly and lack of native language options, as most apps may be available in English, which is not spoken in rural areas in some countries. The limitations of the applications to certain specific projects or research that make them unable to scale properly.

2.3.1.2 Remote sensing technologies

Remote sensing technologies are being deployed in the agricultural sector connected to drones, IoT and satellite imagery to measure spatial variability, plan irrigation and harvesting, and communicate farm conditions throughout the production cycle (Trendov et al., 2019; Schroeder et al., 2021). These technologies are intended to be early warning and disaster risk reduction systems by providing information on crop tolerance to disturbances (e.g. drought, salinity or stress, pest or disease) [Trendov et al., 2019; Schroeder et al., 2021; Krishnan et al., 2020]. Guidance systems, on the other hand, are used with remote sensing technologies to generate more precision in crop management, focusing on the precise positioning and movement of a machine with the support of a Global Navigation Satellite System (GNSS), where equipment can till, plant and apply fertilizers and pesticides through a steering system (Trendov et al., 2019).

Reducing temporal and geographic observation gaps in meteorology and improving local weather forecasts used in agricultural advisory services are two advantages of remote sensing technology in the agricultural sector (Stephenson et al., 2021). In addition, they can be used as a tool for tracking process and result metrics, including measuring yield per acre, soil nutritional status, income stability, and field adaptability to external conditions (Stephenson et al., 2021; Schroeder et al., 2021). The advantages of guidance systems are that they can be utilized on different equipment and in various agricultural applications to be able to work faster, in poor visibility and at night making field operations more accurate than with traditional guidance (Trendov et al., 2019). Therefore, these technologies (remote sensing, IoT, drones and satellite imagery) are vital in the agricultural sector for soil and field analysis, planting, crop spraying, crop monitoring, irrigation and health assessment (Trendov et al., 2019; Schroeder et al., 2021; Krishnan et al., 2020), mainly in developing countries, where the amount of ground-based observations is relatively limited and has been decreasing (Stephenson et al., 2021).

Advanced technologies allow continuous crop monitoring and can help farmers make decisions that improve the efficiency and profitability of their farm, although the main drawback of such technologies is that they are all very expensive, which is a barrier for farmers to acquire them (Trendov et al., 2019; Rejeb et al., 2022). In the case of drones, they cannot operate for many hours and cover large areas because they are limited in terms of endurance, airspeed and adverse weather conditions (Rejeb et al., 2022).

Additionally, the data provided to farmers by remote sensing technologies may be erroneous as a result of inadequate infrastructure support, which can lead to major errors in farmers' decision-making and mistrust within value chain networks (Krishnan et al., 2020). There is a high level of complexity to be able to use these technologies, so farmers need digitally skilled workers, which increases costs, and it is also important to review the issue of cybersecurity (Rejeb et al., 2022).

2.3.1.3 Big Data

Big data is defined by Trendov et al. (2019) as large volume of structured and unstructured data sets with different type of information, including text, numbers, pictures, videos, among other, which must be computationally analyzed to identify trends, associations, interactions and patterns. It is characterized by the 4V’s describing as follows: Volume is the size of the data collected; Velocity is the time window in which the data is useful and relevant; Variety is the heterogeneous sources of data gathered, and Veracity is the reliability of the data (Kamilaris et al., 2017).

Big data is connected to data science and cloud computing to provide information to the final user. Data science makes an effort to prepare, filter, and analyze the intricate patterns found in massive data in order to create models, and cloud computing is one of the most popular methods for filtering and providing trends for huge data (Krishnan et al., 2020). Once the data is processed and analyzed, it can help maximize crop yields while reducing the amount of inputs and human resources used, i.e., the entire agriculture value chain is being transformed by big data (Trendov et al., 2019).

In the agricultural sector, the information that can be collected are relate to weather and climate change, land, crops, soil, weeds, biodiversity, farmer decision-making, farmer finance and insurance, and food availability and security, where information can be obtained through historical information and datasets, weather stations, geospatial data, remote sensing, camera sensors, statistical data, web-based data, financial transaction data, among others (Kamilaris et al., 2017).

However, there are main challenges in the implementation of big data that need to be taken into account. There is no clear consensus on how to protect the data of small and medium-sized farmers, so there are fewer incentives for the implementation of these technologies (United Nations, 2017). The lack of cybersecurity and data protection is a risk for the use of big data because of potential cybersecurity threats that can lead to the introduction of improper functioning of farm equipment or poor decision-making by farmers (Trendov et al., 2019). There is no adequate infrastructure for maintaining connectivity or for data management for small farms, resulting in fragmented data collection due to lack of standardization (Trendov et al., 2019). Large investments are needed in infrastructure for data processing and storage, often requiring real-time operation, which is a barrier for smallholder farmers (Kamilaris et al., 2017). Data management requires specific knowledge for data processing and sophisticated analytical tools, so training of farmers is necessary (Benyam et al., 2021).

2.3.1.4 Integration and coordination systems

Integration and coordination systems have been used to integrate and improve decision-making, operations and information in production and administrative processes in agriculture, which has helped to coordinate the different stages of the food supply chain (Trendov et al., 2019). These systems include blockchain, ERP, and finance and insurance systems.

ERP software helps streamline all processes in the agricultural sector, with the main benefits being the maintenance of business operations, product quality assurance, financial account control and inventory management (Trendov et al., 2019). It can also enable a farm to respond to environmental challenges more organically, modify systems as needed and become a more cost-efficient enterprise.

Blockchain, on the other hand, is a public digital ledger that is an online record of transactions that can be used and shared simultaneously across a large decentralized network that is open to the general public (Schroeder et al., 2021). It enables the secure management and storage of data, improving traceability, efficiency and transparency in the food supply chain. The benefits of using blockchain are proof and verification of geographical origin, certainty of contracts, compliance with sanitary and phytosanitary regulations and traceability of products. According to analysis by the World Economic Forum (WEF), through blockchain traceability it is possible to reduce food loss in food systems by up to 30 million tons per year, if blockchain controlled information in half of the world's supply chains (WEF 2018 cited by Schroeder et al., 2021, p. 84).

The challenges faced by integrated and coordinated systems include regulatory uncertainty and lack of trust among users due to the depersonalization of contracts (Trendov et al., 2019; Schroeder et al., 2021), which makes it difficult to implement these digital solutions. These systems have new techniques that imply high implementation costs and it is not easy to confirm whether the long-term benefits outweigh the costs. It also requires reliable connectivity between different stages of the supply chain to transmit information, as well as physical and digital infrastructures and digitally skilled workers (Schroeder et al., 2021). Similarly, supporting technologies are needed to implement these digital solutions (United Nations, 2017).

2.3.1.5 Intelligent systems

Intelligent sensors and autonomous robots increase accuracy in agricultural activities, such as crop yield prediction, disease and pest detection, quality recognition, weather forecasting, and water and soil management (Trendov et al., 2019). These systems are Deep Learning, Machine Learning, AI, and robotic and autonomous systems.

Deep learning is the application of artificial neural network architectures with numerous processing layers, which are mathematical models with the capacity to be trained through the process of supervised learning (Ferentinos, 2018; Schroeder et al., 2021). In the agricultural sector, it is mainly used for image recognition and plant disease diagnosis (Trendov et al., 2019).

Machine learning is a method of data analysis that endows machines with the ability to learn from experience, i.e. it automates the construction of analytical models without being strictly programmed to perform a task and with minimal human intervention (World Bank Group, 2019). Uses of ML in the agricultural sector are for crop management, including yield prediction, disease and weed detection, crop quality maintenance, and water and soil management (Trendov et al., 2019).

AI is the theory and creation of computer systems that can perform tasks that often require human intelligence by adjusting machines to obtain new data to enable them to execute human-like tasks (Schroeder et al., 2021). In the agricultural sector, with AI farmers can make data-driven decisions to maximise production, they can scan their fields and track every step of the production cycle, predict weather, manage water efficiently and anticipate pest control (Trendov et al., 2019).

Robotics handle the design, production and application of robots together with automated systems developed for information processing, sensory feedback and control (Schroeder et al., 2021). In agriculture, robots can optimise water use and irrigation, decrease the use of pesticides and fertilizers, reduce the impact on soil quality and the use of additional inputs, achieving an overall reduction in environmental impact while monitoring crops and controlling weeds (Trendov et al., 2019).

The challenges of these systems are varied, there is a global lack of knowledge about the opportunities for intelligent systems in agricultural application, as well as the need for large datasets to predict information, which are difficult and time consuming to collect (Trendov et al., 2019). In addition, stable connectivity and electricity, and digital infrastructure and technical support, are indispensable for the smooth functioning of the technologies (World Bank Group, 2019), which are not available in developing countries, especially in rural areas. Furthermore, training of employees to generate specific skills are needed to operate the systems along with the transformation process in the value chain that enables the incorporation of intelligent systems (World Bank Group, 2019; Trendov et al., 2019). There is a risk of employment transformation that can be drastic for rural areas in the farming system, where repetitive process jobs are eliminated in exchange for technical positions to be able to control the systems (United Nations, 2017; Benyam et al., 2021; Trendov et al., 2019). Lastly, there is the threat of decreasing crop diversity and move towards monocultures to operate more efficiently with these smart systems to have greater control of outcomes with fewer variables (Schroeder et al., 2021).

2.4 Conclusion

This chapter provides an overview of how the agricultural sector has developed, including the consequences on the environment and how food loss plays a key role in generating some of these negative consequences. Food loss has a huge economic, social and environmental impact due to the increased use of land, water and energy to produce additional food to compensate for food that does not reach the final consumer. Food is often lost along the food supply chain, generating more waste and pollution, which also contributes to climate change, land-use change, freshwater depletion and biodiversity loss.

Measuring food loss is not easy due to the lack of a common definition and standard methods around the world, which reduces the availability to compare studies between countries and to understand the problem of food loss. At the same time, there is not enough research to be able to recognize the exact amount of food loss that is generated worldwide. However, the main causes (e.g. overproduction, premature harvesting, delayed harvesting, improper handling, inefficient infrastructure and weather conditions) have been identified.

There is an ongoing challenge in the agricultural sector, with an estimated 10 billion people to be fed by 2050, implying an expansion of agricultural production by 70 percent (FAO, 2019; FAO, 2018; Aznar-Sánchez et al., 2020a; Velasco-Muñoz et al., 2021). At the same time, 3.1 billion people worldwide lack access to healthy food and 828 million go hungry (FAO, IFAD, UNICEF, WFP and WHO, 2022). This means that the agricultural sector is neither sustainable nor efficient and by reducing food loss, availability and access to food can be improved.

Sustainable agricultural practices can help to have a lower impact on ecosystems, creating a sector that is less dependent on non-renewable energy sources. Digital agricultural technologies can also support facilitate distribution processes and improve communication along the entire food supply chain. However, there are some barriers to the implementation of both that need to be considered in order to overcome them, just as the implementation of these practices requires a certain level of knowledge and investment.

Addressing food loss in the agricultural sector has different approaches depending on geographical, socio-economic and political conditions. In order to assess food loss in the agricultural sector, it is important to focus on a country or region, a specific product and the part of the supply chain where it has occurred. Thus, on-farm production in the rice sector in Colombia is selected in this research, as this crop is considered a staple food for more than half of the world's population, not only as a source of nutrients and energy, but also as a source of work and income.

The agricultural sector needs to be reformed to be able to feed the world's population while reducing impacts on the environment. In this way, natural resources and energy will be used efficiently, while production will have less impact on land, freshwater and the environment. There are not only sustainable agricultural practices that can be applied in the rice sector to improve its production, but also digital agricultural technologies. However, before making any decisions, the empirical part of the thesis evaluates what sustainable practices and digital agricultural technologies can be implemented in the rice sector in Colombia to become more sustainable, taking into account their benefits and risks.

3 METHODOLOGY

3.1 Introduction

This section is used to present the research methodology and how data are collected and analyzed. The starting point of the research design and what determines the research approach is the research question. It explains what the author wants to answer taking into account time and resource constraints (Robson, 2011). Depending on how the research question is formulated, the answers can be exploratory, descriptive or explanatory, and the answer should be consistent with the flow of the research. The research question to be answered is:

What types of digital technologies are best suited to support the agricultural sector in Colombia on the way towards sustainable practices with the aim of reducing food loss?

The aim of this study is better understanding the role of digitalization in the agricultural sector in Colombia – focusing on the rice production – and to suggest best practices for the implementation of digital agricultural technologies and environmentally friendly practices to achieve a reduction of food loss in the country and reach sustainable agricultural production. Therefore, the research question must be answered in an exploratory manner because it is a means to discover "what is happening; to seek new insights; to raise questions and evaluate phenomena in a new light" (Robson, 2002, p. 59 cited by Saunders et al., 2007, p. 133). As Neuman (2014) states, the goal of exploratory research is to develop precise questions to be addressed in future research, so with this research it is possible to create a general mental picture, generate new ideas, establish the feasibility of conduction a research and develop techniques to measure data. An advantage of this purpose is flexibility and adaptability to change depending on the data collected.

3.2 Research approach

Research design is the logic involving the plan and process for conducting an empirical investigation. Based on the work that John Cresswell developed on research design, shown in the figure 2, there are identified three types of approaches to conducting research: quantitative, qualitative and mixed methods. Those can be chosen depending on different aspects of the research such as: the basic philosophical assumptions brought to the study, the types of research strategies used in the research and the specific methods employed in carrying out these strategies (Creswell, 2009). The research design begins with the research question and is the starting point for choosing the philosophical worldview, the methods, and the strategy of inquiry. The researcher must reflect on the philosophical worldview to choose the inquiry strategy and the methods applied to turn the research question into a project (Cresswell, 2009).

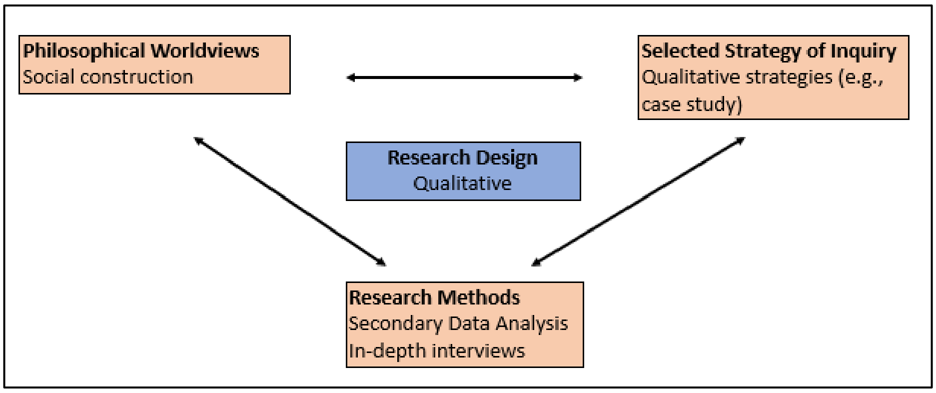

FIGURE 2: A FRAMEWORK FOR DESIGN—THE INTERCONNECTION OF WORLDVIEWS, STRATEGIES OF INQUIRY, AND RESEARCH METHODS (ADAPTED AFTER FIGURE 1.1 BY CRESWELL, 2009, P. 5).

Source: Creswell, 2009, p. 5

The research approach is a plan that includes the steps for data collection, analysis and interpretation. The major differences between quantitative and qualitative research are, "(1) the distinction between explanation and understanding as the purpose of inquiry; (2) the distinction between a personal and impersonal role for the researcher; and (3) a distinction between knowledge discovered and knowledge constructed" (Stake, 1995, p. cited by Jackson et al., 2007, p. 22). While mixed methods encourage to implement multiple approaches to data collection, i.e., quantitative and qualitative methods to complement each other (Cresswell, 2009).

In this thesis, a qualitative design is the most feasible approach because it aims to explore and comprehend the meaning that specific groups (i.e., stakeholders in the agricultural sector) attribute to a social problem (unsustainable production leading to food loss). The research process involves the author's interpretation of data once it has been collected – from multiple sources – reviewed, organized and categorized, which implies a flexible structure as additional questions and procedures arise during the research process (Creswell, 2009)

3.3 Philosophical worldview

As pointed out by Creswell (2009), the philosophical worldview needs to be identified because influence the research process including the selection of methods, as it is "a system of beliefs and assumptions about the development of knowledge" (Saunders et al., 2019, p. 130). Creswell identified four: postpositivism, constructivism, transformative and pragmatism. In this study, the research design is guided by the social constructivism worldview, as it deals with the real world contexts which are inmerse in a social construction, i.e., people want to comprehend the environment in which they live and work, so they generate subjective meanings of their experiences, which are diverse and multiple. The aim is that the researcher focusses on the complexity of the view rather than try to categorize or organize them (Creswell, 2009).

The approach chosen to theory development, could be inductive or deductive, depending on how the theory is implemented and the data analyzed. In this study, the approach is inductive because it provides an efficient way to analyze qualitative data and aims to help understand the meaning of complex data. As Thomas (2006, p. 1) states, the purposes of an inductive approach are three, "(1) to condense extensive and varied raw text data into a brief summary format; (2) to establish clear links between the research objectives and the summary findings derived from the raw data and (3) to develop a model or theory about the underlying structure of experiences or processes which are evident in the raw data". So being a type of research with a relatively new and complex topic, this is the best approach.

3.4 Research strategy: case study

The strategy of inquiry is a type of study that offers guidance for procedures in the research design (Cresswell, 2009, p. 11) and is consistent with the philosophical worldview. It focuses on data collection, analysis and writing. Creswell (2009) divides the strategies of inquiry in three categories: (a) quantitative (e.g., experimental designs and non-experimental designs) (b) qualitative (e.g., narrative research, phenomenology, ethnographies, grounded theory studies and case study) and (c) mixed methods (e.g., sequential, concurrent and transformative).

For this thesis, the selected inquiry strategy is a case study. As Rowley (2002) points out, it is an empirical inquiry in which contemporary phenomena are investigated in their connection to real life, which is enriched with multiple sources of data, including documents and interviews. It is an in-depth investigation of a topic over a period of time, in which it is possible to discover the relationship between different social, cultural, economic and political factors that are connected to the phenomenon of interest (Bhattacherjee, 2012).

Therefore, it is a comparative case study between two developing countries – Colombia and Kenya – with a similar location with respect to the tropic, but with different approaches to agriculture. In a comparative case study, "the objective is to compare or replicate the organizations studied with each other in a systematic way, in the exploration of different research issues" (Rowley, 2002, p. 17). Colombia has focused on improving agronomic crop practices through capacity building, technical assistant and technology transfer, while Kenya has focused on improving rice varieties through technology and the introduction of digital entrepreneurships to improve productivity. The scope of the case study focuses on agricultural production (pre-harvest, harvest and post-harvest) in the rice sector. Rice is considered the third most important crop in both countries and is a primary source of employment and income in rural areas. The objective of the case study is to compare practices to provide some recommendations on sustainable agricultural practices and digital agricultural technologies.

The advantage of using a case study is the possibility of applying a combination of qualitative and quantitative data, such as interviews and document analysis, collected from different sources and with different methods (Bhattacherjee, 2012; Rowley, 2022). Creswell (2009) also indicates that in the case study as a strategy of inquiry the researcher "explores in depth a program, event, activity, process, or one or more individuals" (p. 17), which is bounded by time and activity. This is in line with the master thesis, as it investigates the evolution of the agricultural production, focusing on rice sector in on-farm production in the two countries over a time period of 20 years, from 2000 to 2020.

3.5 Research methods

Research methods are techniques for collecting, analyzing and interpreting data (Robson, 2011; Creswell, 2009). As Kaplan (1964) states, method "refers to the tools, techniques, or procedures used to generate data" (Jackson et al., 2007, p. 25). Creswell (2009) categorizes them according to the type of research approach, i.e. quantitative, qualitative and mixed method. Each has different types of data collection, as well as their form of analysis and interpretation, as shown in Figure 3. The methods used in this thesis are document analysis and expert interviews.

Quantitative Methods	*Mixed Methods*	*Qualitative Methods*
• Pre-determined • Instrument based questions • Performance data, attitude data, observational data, and census data • Statistical analysis • Statistical interpretation	• Both pre-determined and emerging methods • Both open- and closed-ended questions • Multiple forms of data drawing on all possibilities • Statistical and text analysis • Across databases interpretation	• Emerging methods • Open-ended questions • Interview data, document data, and audio-visual data • Text and image analysis • Themes, patterns interpretation

TABLE 2: QUANTITATIVE, MIXED, AND QUALITATIVE METHODS

Source: Creswell, 2009, p. 15

The first step to answering the research question is to conduct a literature review, where definitions of food loss, sustainable practices and digital technologies in the agricultural sector are given. This is followed by documentary analysis. The aim is to gain a better understanding of the current state of sustainable agricultural practices and digital agricultural technologies used in the rice sector in Colombia and Kenya. The information is mainly gathered from reports, research papers and statistical data. Through this process, it is possible to find out the best practices implemented in Kenya and provide recommendations to the main case Colombia.

Then, in-depth expert interviews with open-ended questions are conducted to validate with stakeholders the recommendations provided to Colombia from Kenya. Semi-structured interview are applied to allow participants to share information related to the formulated topic following a guide of main points to cover. The questions are based on a thematic guide focusing on the expert's knowledge of a certain field of action (Döringer, 2020), however, further questions can be added depending on the flow of the interview. Document analysis is frequently used in combination with other qualitative research methods – in this case in-depth expert interviews – to establish validity through triangulation (Bowen, 2009).

3.5.1 Documentary analysis

Bowen (2009) defines document analysis as a a systematic review to evaluate documents and interpret data in order to obtain meaning, understanding and knowledge of the selected data. In this sense, the researcher can lessen the influence of any potential biases that may exist in the study by correlating findings across data sets and looking at information gathered using various approaches (Bowen, 2009, p. 28). In this study, it is used as a systematic review, in which multiple data sets are used to provide an overall assessment of the findings on the status quo of the rice sector in on-farm production, regarding the use of sustainable agricultural practices and digital agricultural technologies in Colombia and Kenya. Through secondary analysis of comparable data, it is possible to conduct cross-cultural research due to being able to contrast two or more countries (Bryman, 2012).

As Bowen (2009) points out, the advantages of using document analysis in qualitative research are the availability of documents online and in public domain, the reduction of time spent because data are selected rather than collected, cost-effectiveness because the data are already collected so it is a less expensive method, and the stability of the documents and accuracy of the information because the data are already studied and cannot be influenced; while the disadvantages are the low retrievability of the documents because they are usually locked, the documents do not provide enough details and the possibility of biased selectivity when choosing the documents.

3.5.1.1 Documentary data collection:

In the thesis, the document analysis is done though the bibliographic search of secondary sources such as books, scientific articles, review articles and reports, in sources like Google Scholar, ScienceDirect and CGIAR. The search syntax used includes search terms such as 'digital agricultural technologies' and 'sustainable agricultural practices' combined with 'rice' and 'Colombia' or 'Kenya'. For the case of Colombia, the search is in Spanish and for Kenya in English and the time period is 20 years, from 2000 to 2020. Some examples are 'digital agricultural technologies + Colombia + rice' and 'sustainable practices + rice + Kenya', where 478 documents are found for the case of Colombia and 356 for the case of Kenya.

3.5.1.2 Documentary data recording:

The data is recorded in an excel file in order to organize the information and compare the case of Colombia with the case of Kenya. In the table of sustainable agricultural practices for both cases, a problem is identified where a solution is implemented and the economic, social and environmental impacts are explained (See Appendix 3 and 4). As for the table of digital agricultural technologies for both countries, a problem is also detected where a digital technology is used and the solution is explained (See Appendix 5 and 6). Through these tables it is possible to recognize the status quo of rice production in both countries.

3.5.1.3 Documentary data analysis:

The first classification of documents is done by reading the abstract, the key words, the main findings and the conclusion with the objective of choosing the documents that can be used to compare the cases of the two countries considering the years of research (2000 – 2020), the product (rice) and the part of the supply chain (on-farm production: pre-harvest, harvest and post-harvest). The documents used in the documentary analysis to compare Colombia and Kenya can be found in Appendix 3 and 5 (for Colombia) and 4 and 6 (for Kenya). In the next step, ten recommendations from the Kenyan case to be implemented in the Colombian case are found (See Appendix 7), which are validated through in-depth interviews with experts.

3.5.2 Expert interviews

Expert interviews is an empirical step, collecting information from primary sources and complementing the case study information with the experience of the interviewees regarding the current problems of food loss in the country, the state of development of sustainable agricultural practices and the state of application of digital agricultural technologies. As Baym (2005) points out, the choice of the in-depth interview method takes into account the topic under investigation, how the information is generated and which procedures are best suited to produce the results sought by the author (James & Busher, 2009).

The interviews are used because the participants can provide the historical information of the agricultural sector in Colombia and add what are the needs of rice production where sustainable practices and digital technologies are required. However, according to Creswell (2009), the limitations of this method are the obtaining of information filtered through the interviewees' perspectives, the focus on a case with a predetermined environment rather than on a natural environment, a possible bias due to the presence of the researcher when answering the questions, and that not all people are equally eloquent and insightful.

As a first step, the segment of the population is selected through a mapping of the stakeholders working for sustainable agriculture in Colombia based on information from the literature review and the case study. Public entities, affiliated entities, unions or associations and NGOs or non-profit organizations (NPOs) are considered. The objective is to interview different organizations that work directly with farmers and also in contact with different actors. After gathering the potential candidates for the interview, the selection is done through expert sampling, which is a non-probabilistic approach, where participants are chosen based on their involvement with the topic and their willingness and ability to provide accurate and comprehensive answers (Bhattacherjee, 2012). The elements studied involved the identification of problems in the agricultural sector that hinder its economic, social and environmental performance, as well as experience with farmers in the application of sustainable practices and digital technologies.

The experts chosen belong to public entities, unions or associations, NGOs and NPOS working on projects to make agriculture in Colombia more sustainable, to whom the recommendations are presented in order to reach a point of feasibility. All contacts are sought mainly through the internet, either through the official websites of the organizations or through social networks such as LinkedIn. They are contacted by email to schedule an online meeting, where they are sent an interview guideline so that they have the necessary material to prepare before the meeting. The interviewees are listed in Table 3.

The sample size is defined by the saturation of the data, i.e., when respondents mention similar answers that can be grouped together and no new information is discovered in the data analysis. Saturation is visible after starting the interview process and conducting the first five interviews. On the other hand, the validation of the selection is done through snowball sampling, since when the first participants were interviewed, they recommended organizations that had already been found in the stakeholder mapping and contacted by the researcher, although not all of them responded to the invitation.

Experts Interviews			
Interview	*Organization*	*Type of organization*	*Role*
(I1)	Asociación de Corporaciones Autónomas Regionales y de Desarrollo Sostenible (ASOCARS)	Non-profit organization	Biologist in charge of national agreements
(I2)	Dignidad Agropecuaria Colombiana (DAC)	Non-profit organization	National Executive Director
(I3)	Federación Nacional de Arroceros (FEDEARROZ)	National trade association	Research engineer, technical assistance and technology transfer
(I4)	Ministerio de Agricultura y Desarrollo Rural (MADR)	Government Institution	Technology, Information and Communications Office Chief (Ministry approach)
(I5)	Unidad de Planificación Rural Agropecuaria (UPRA)	National entity attached to the Ministry of Agriculture	Technical Advisor (UPRA approach)
(I6)	Unidad de Planificación Rural Agropecuaria (UPRA)	National entity attached to the Ministry of Agriculture	Technical director for efficient land use and land suitability (UPRA approach)
(I7)	Fondo Nacional del Arroz (FNA) en la Federación Nacional de Arroceros (FEDEARROZ)	Entity affiliated to Fedearroz	Agronomist in charge of research and technology transfer in rice cultivation.

TABLE 3: INTERVIEWEES

Source: own work

3.5.2.1 Data collection:

The author uses semi-structured interviews, based on a list of open-ended questions to be asked in a specific order (Bhattacherjee, 2012; Bryman, 2012) called an interview guideline. It is shared with individuals prior to the interview so that they can familiarize themselves with the topic and questions. In the first part, questions are asked on three specific topics: food loss, sustainable agriculture and digitalization in agriculture, all based on the case of Colombia. In the second part, ten recommendations from the Kenyan case are asked to be evaluated for the Colombian case –

with a focus on on-farm rice production – in order to be validated according to the perspective and experience of each interviewee. Recommendations are chosen which, according to experts, can help rice production to become more sustainable by reducing food loss during on-farm production. The aim is to understand how the interviewees interpret the questions and give their answers by emphasizing the aspects they consider important and the way they explain events, patterns and forms of behaviour (Bryman, 2012). See Appendix 8 for the interview guideline.

3.5.2.2 Data recording:

Interviews are audio-recorded with the consent of the interviewees. In case the recording is lost or cannot be played back, the researcher takes notes while conducting the interviews. Additionally, note-taking by the interviewer is important to capture key comments or critical observations of the interviewee (Bhattacherjee, 2012) which is used for data analysis. As Bryman (2012, p. 482) mentions, “qualitative researchers are frequently interested not just in what people say but also in the way that they say it”.

3.5.2.3 Data analysis:

According to Creswell (2009), the process of data analysis involves preparing the data, understanding it, representing it, and interpreting it, i.e., making sense out of the data collected. In this thesis, once the in-depth interviews are conducted, the interviews are transcribed using the notes of the interviewer and the audio recordings. They are then organized in an Excel table by themes to be able to read them, they are translated and, subsequently, coding begins.

As Rossman & Rallis (1998) point out, coding is the process of organizing the material into segments before making sense of the information (Creswell, 2009). Codes are assigned to sentences to group similar ideas that are compared to the case study and analyzed in the discussion of the findings. The coding process is done for each question individually, similar responses are given the same color to differentiate answers among respondents and identify which ones are repeated. See coding in Appendix 9. In the interview analysis, the organizations the respondents work for are described to differentiate stakeholder perspectives based on the projects they work on. Then a compilation of the problems in the rice sector and suggestions for improvement according to the experts is provided.

In the discussion of the findings, the information collected in the case study is compared with the expert interview to provide an analysis of the current status of the three themes, as well as the challenges and implementation of the latter two. For the assessment of the recommendations, a qualitative book is created, which according to Creswell (2009), is a table containing a list of themes used to code the data. It is a code that emerges during the analysis of the data (Creswell, 2009), and helps to divide the problems of the rice sector into economic, social or environmental to emphasize what can be improved. As a last step, the information provided in the table with the main problems in the rice sector is used to evaluate the level of environmental emergency that addressed by the implementation of the recommendation, as well as what level of knowledge and level of investment is needed for farmers to implement the given recommendations. Conclusions are presented with recommendations provided by the author, unifying the documentary analysis and in-depth interviews with the literature review. In addition, the limitations of the research are presented and other research possibilities are offered.

3.6 Strategies for establishing validity

Due to the possible bias that may occur throughout the research, since it is a qualitative research, it is important to consider validity and reliability at all points of the study. As noted by Bhattacherjee (2012), “reliability and validity, jointly called the “psychometric properties” of measurement scales, are the yardsticks against which the adequacy and accuracy of our measurement procedures are evaluated in scientific research” (Bhattacherjee, 2012, p. 55). On the one hand, reliability focusses on the consistency of findings across data collection. On the other hand, validity focuses on whether the findings are what they appear to be (Saunders et al., 2007).

As Rowley (2002) points out, there are three principles that must be followed during data collection – regardless of the source chosen – to establish validity. Those are triangulation, case study database and chain of evidence. Triangulation is used to confirm the same finding with different sources; case study data base is used to assemble the collected evidence; and chain of evidence is used to clearly and precisely demonstrate which sections of the case study databases are used in the research, involving citing appropriately (Rowley, 2002). Therefore, it is important to document all processes that take place during the research. Similarly, different strategies can be used, e.g., conveying the information of the results with a rich and detailed description; clarify the researcher's bias in the study by emphasizing how her context and background may influence the results; use peer feedback to improve the accuracy of the results (Cresswell, 2009).

According to Rowley (2002), to determine the quality of empirical social research, the following four tests have been commonly used:

- Construct validity: it examines the precision with which a given measurement scale measures the expected findings (Bhattacherjee, 2012). It is achieved by relating the data collection questions and measures to the research questions and propositions, thus aiming to expose and reduce subjectivity (Rowley, 2002).
- Internal validity: It establishes a causal relationship that demonstrates that certain conditions lead to other conditions, as opposed to spurious relationships (Rowley, 2002). It requires three conditions: covariation of cause and effect, temporal precedence and absence of plausible alternative explanation (Bhattacherjee, 2012).
- External validity: it determines the domain in which a study's outcome can be generalized from the sample to the population, or to other people, organization, contexts, or time (Rowley, 2002; Bhattacherjee, 2012). Generalization can only take place if the case study design has been adequately grounded in theory and can therefore be seen to add to established theory, in which the empirical findings of the case study are tested against a previously developed theory (Rowley, 2002).
- Reliability: It demonstrates that the process of the study, including data collection, can be repeated and with the same results (Rowley, 2002), i.e. the research approach is consistent throughout the research flow (Creswell, 2009).

4 CASE STUDY OUTLINE

This chapter contains the empirical part of the study. The author has chosen two countries, one in Latin-American and one in Sub-Sahara Africa, with a similar geographical location to the tropics but different approaches to agriculture. Table 4 shows general comparable data for both countries, to get an overview of their similarities and differences. First, a general description of the countries including geographic and demographic aspects, succeeded by economic and social aspects is provided. Then, the historical agricultural development of both countriesis presented, followed by the impact of agriculture on the environment considering the land and water use, adding the most recent information on food loss in each country according to national studies. The last section describes the rice production in each country taking into account sustainable agricultural practices and digital agricultural technologies applied in each case.

Parameters	*Colombia*	*Kenya*
Physical area		
Surfaces (km²)	1,141,748	580,370
Agricultural land (percentage of land area)	43.5	45.5
Forest area (percentage of land area)	53.3	6.3
Population		
Population	51,516,562	53,005,614
Population density (inhabitants/km²)	46.4	93.1
Population employed in agriculture	4,17 million	12,9 million
Population livinng in rural areas (percentage)	18	72
Total formal employment from agriculture (percentage)	16	54
Economic and Development		
GDP (US$/year)	314,46 billion	110,35 billion
Agriculture, forestry, and fishing, value added (percentage of GDP)	7.4	22.4
Human development index	0.77	0.60
Gini coefficient	0.54	0.59
Informal employment (percentage)	58.2	77
Food security		
Chronic malnutrition (of children under 5) [percentage]	12.7	26.2
Insufficient food consumption	19 million	10.4 million

TABLE 4: COMPARISON OF BOTH COUNTRIES

Source: own work based on information from DANE, DNP, Economist Impact, FAO, Our wolrd in data, WFP and World bank.

4.1 The agricultural sector in Colombia

Colombia is considered a megadiverse country due to its high environmental variability (Etter et al., 2006), hosting almost 10 percent of the planet's biodiversity (Convention on Biological Diversity, 2020). It is located in the northwestern corner of South America and the total continental area is 1,141,748 km² (FAO, 2015b), with 43.5 percent of the land area being used for agriculture and 53.3 percent for forestry (World Bank, 2021a).

The country comprises five major biogeographic regions, the Andes (278,000 km²), the Caribbean (115,400 km²), the Pacific coast (74,600 km²), the Colombian Amazon (455,000 km²) and the Orinoco Plains (169,200 km²), and has coastlines on the Pacific and Atlantic oceans (Etter et al., 2006), but its topography is dominated by the Andean mountains. Due to its location near the equator, it has no seasons, so the country's temperature varies according to altitude above sea level. Colombia, because of its regions, also presents a great variety in altitude (0 - 5800m), in mean annual precipitation (300 - 10,000 mm) and in the length of the growing season [60-360 days per year] (Etter et al., 2006).

The country's economy is based on trade, industry, construction, transport, agriculture and mining (Gobierno de la Republica de Colombia, 2019). The GDP of Colombia in dollars is 314,46 billion, of which 7.4 percent corresponds to the agricultural sector (World Bank, 2021a), the main crops for the country are sugar cane, palm oil fruit, raw milk of cattle, rice, potatoes, and bananas.

In Colombia, there are around 45 million hectares available for agricultural economic activity (agroforestry, agriculture and livestock), however, land use data show that the area dedicated to agricultural activities is 31.9 million hectares. Of these, 7.11 million hectares are used for agricultural crops (transitory and permanent), 24.8 million hectares are savannahs and natural pastures, 11 million hectares are fallow and stubble areas and 63.2 million hectares are natural forest areas (Perfetti del Corral, 2022b). Therefore, there is a high availability of agricultural land in the country, but only a quarter of this land is used, leading to a phenomenon of underutilization of this resource, while livestock activity uses more than 50 percent of the available land (Perfetti del Corral, 2022b). This leads to a land use conflict that leads to inefficient land use.

According to World Bank data from 2021, Colombia has a population of 51,516,562 inhabitants (World Bank, 2021a), with a population density of 46.4 (inhabitants/km2) [Our world in data, 2023a], of which 18 percent live in rural areas (World Bank, 2021a). Of these, 4,17 million are employed in agriculture (Our world in data, 2023a), accounting for 16 percent of total formal employment (World Bank, 2021a). According to the Human Development Index, the country has a score of 0.77 (Economist Impact, 2023), ranking 88th out of 191 countries in 2021/2022 (WFP, 2022a), at the same time, inequality in the country is high, with a Gini index of 0.54 (World Bank, 2021a) and informal employment is 58.2 percent, according to national studies (DANE, 2023).

Population distribution is highly concentrated in the north and west, where natural resources and agricultural opportunities are found, with more than three-quarters of the population occupying less than 30 percent of the territory (FAO, 2015b). It is also estimated that 80 percent of farmers belong to family farming and produce 79 percent of the food consumed in the country, with 30 percent of this group being women (WFP, 2021). The agricultural sector is the largest source of employment in rural areas and the third largest employer in the country (Cárdenas Pinzón, & Vallejo Zamudio, 2016).

As reported by the World Food Programme (WFP), Colombia faces a complex humanitarian situation that puts the country's performance at risk, with violence by illegal organized armed groups, illegal economy, extreme natural events, a massive migration crisis, high inflation, currency devaluation and social and economic impacts of the COVID-19 pandemic (WFP, 2021; WFP, 2022a). In fact, "one in three Colombian households, and three in four pendular migrants and people in transit are food insecure" (WFP, 2022a).

According to the WFP hunger map, 19 million people have insufficient food consumption and 12.7 percent of children under 5 years of age are chronically undernourished (WFP, 2023). Hence, resilience and adaption to climate change are needed in the country to improve food security and nutrition, but Colombia's environmental vulnerability is high due to deforestation, increasing water scarcity, informal human settlements and pollution of rivers and ecosystems mainly from rural activities (WFP, 2021).

4.1.1 Development of the agricultural sector

Colombia's agricultural problems are an evidence of the institutional, political and social instability that the country has faced throughout its history (Beintema et al., 2006). From the end of World War II until 1955, the Colombian economy enjoyed good growth driven by coffee exports (Kalmanovitz & López, 2003). Then, the period from 1950 to 1980 was characterized by the creation of national production protection regulations to promote industrialization and economic growth. It was the time of the expansion of commercial agriculture and also of the decline of coffee (Bálcazar, 2003).

Both importable transitory crops (e.g. sorghum, cotton, soybeans, yellow maize, barley and rice) and permanent export crops (e.g. bananas and flowers) or products with competitive advantages in the domestic market (e.g. sugar and African palm) benefited from specific trade protection measures, which were mainly concentrated on importable goods and, to a lesser extent, on exportable ones (Bálcazar, 2003). Transitory crops, particularly cereals, gained prominence, and the dynamism of sugar cane growth was notable (López Enciso, 2022). But there was another group of products that did not benefit from these agricultural policies (e.g. fruits, vegetables, tubers and pulses, among others), which evolved in line with the dynamics and modernization of the domestic market (Bálcazar, 2003).

Between 1960 and 1970, agriculture was viewed as the engine of progress, the green revolution was implemented and the agricultural extension was mechanized (Bálcazar, 2003). Rice is consolidated as an important transitory crop favored by the agreements between the International Center for Tropical Agriculture (CIAT) and the Colombian Agricultural Institute (ICA) to produce improved seeds, along with the use of fertilizers and machinery (López Enciso, 2022). In the period between 1970 and 1980, the agricultural process of the rice sector required a large amount of chemical inputs and industrial equipment, resulting in considerable dependence on non-agricultural resources, however, yields, measured in tons per hectare, increased considerably (López Enciso, 2022).

Subsequently, between 1980 and 1990, the benefits of green revolution innovations dried up and rice yields stagnated. The years were not good for the agricultural sector because the sectoral composition changed again. The share of transitory crops in the value of production returned to what it had been fifty years earlier, and rice production was mainly dedicated to the domestic market and continued to suffer from competitiveness problems (López Enciso, 2022).

Since the beginning of the 1990s, Colombia has been dealing with a number of major social and economic difficulties, which have influenced the overall economic condition as well as the performance and funding of the agricultural research system in particular, which diminished over the years (Beintema et al., 2006). At the same time, the country also faced the challenging problem of becoming competitive in international markets while adjusting to tariff protections that were first implemented during World War II (Beintema et al., 2006; Kalmanovitz & López, 2003). Credit costs increased as interest rate subsidies for agricultural producers were eliminated, which in turn worsened the country's competitiveness. Between 1990 and 2001, the country's agricultural area was reduced by more than 840,000 hectares, however, the growth of permanent crops (with the exception of coffee) more than compensated for the decline in transitory crops, thus increasing overall agricultural production (Bálcazar, 2003).

From 2000 onwards, the agricultural policy focused on increasing production and facilitating private investment, while promoting the signing of trade agreements with other countries, especially the Free Trade Agreement (FTA) with the United States, which generated a lot of rejection among agricultural trade unions (Junguito Bonnet, 2022). Despite the importance of the agricultural sector in Colombia, it did not perform well between 2010 and 2014, due to its loss of share in GDP, which prevented it from fulfilling basic functions in the country's overall development process. The main causes of this result were a poor policy mix, a weak institutional framework, lack of adequate infrastructure, difficulties of access to land, rural conflicts and insecurity (Junguito Bonnet, 2022). The country's agricultural growth from 2000 to 2013 showed relatively low rates and a downward trend, with growth below the Latin American average (Perfetti del Corral, 2022a).

According to a study from 2014 to 2018, only 24.1 percent of the country's agricultural potential is utilized, while there are land use conflicts between the different agricultural sub-sectors, resulting in low growth and inadequate use of natural resources, generating rural poverty as a constant problem (Perfetti del Corral, 2022a). After the signing of the peace agreement with the guerrilla FARC in 2016, the country achieved rural development because the government was able to reach lands that were previously used for illicit crops (Cárdenas Pinzón, & Vallejo Zamudio, 2016). However, there is still much to be done to achieve land redistribution and sustainable agricultural production.

4.1.1.1 Impact of agriculture on the environment

Agriculture is one of the activities causing the loss of biodiversity due to deforestation, soil erosion as a consequence of monocultures in enormous extension, and the contamination of natural resources by the irrational use of pesticides (Ramírez Vallejo, 1998).

The green revolution transformed agriculture through technological innovation, which increased the productivity, profitability and competitiveness of crops, especially cereals. The integration of genetically modified seeds, for example, produced more crops in less land, because they are more resistant to pests and adverse climatic variations, which increased crop yields (Medina Medina, 2017). However, the modernization of agricultural production also increased the excessive use of fossil fuels energy, heavy machinery, agrochemicals, monoculture and irrigation (Medina Medina, 2017). The green revolution also generates dependence on genetically homogeneous seeds, which increased the salinization and alkalization of water resources, affected the health of people who work with agrochemicals and favored farmers with greater economic capacity, leaving small-holder farmers aside.

4.1.1.1.1 Land use

Colombia has been a major contributor to the world's agricultural production since the 1980s (OECD and FAO, 2015 cited by Mbow et al., 2019). This has generated an expansion of agriculture that has increased deforestation rates in the region transforming the original landscape. Figure 4 shows the loss of tree cover in Colombia from 2001 to 2021, during this period 4.93 million hectares were lost, which is equivalent to a decrease of 6 percent of the total tree cover (Global Forest Watch, 2021a). The two regions where agricultural production is one of the main sources of deforestation are the Andean region, for the cultivation of coffee, fruits, banana and sugar cane and transitory crops such as potatoes, peas and beans; and the Orinoquia region, where land has recently been transformed for agricultural activities including the cultivation of rice, corn, African palm and fruits (Garcia, 2014).

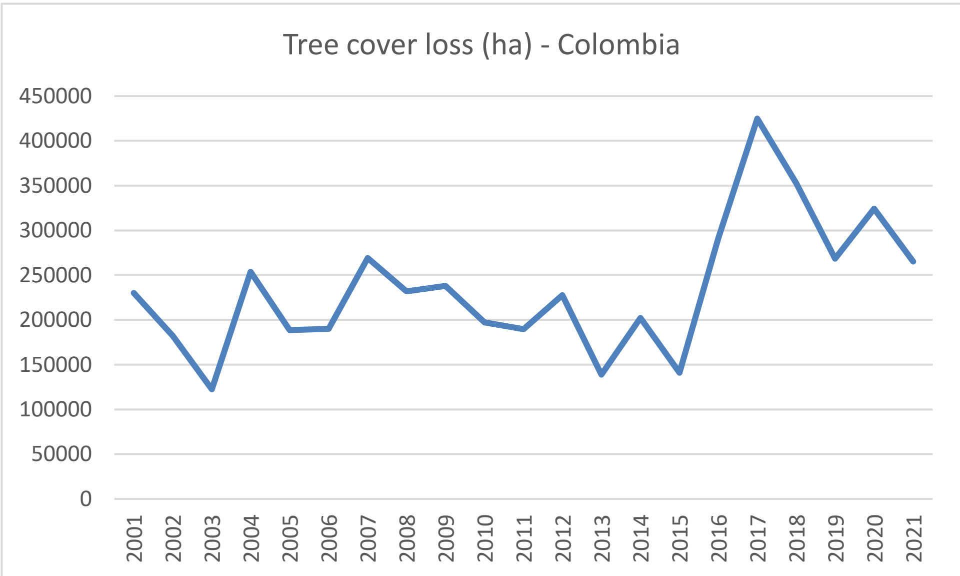

FIGURE 3: TREE COVER LOSS IN COLOMBIA

Source: Global Forest Watch, 2021a

Due to the biodiversity of the country, there is a great contrast in biophysical characteristics and land use patterns between the different regions of the country, which leads to different deforestation dynamics (Etter, 1998; Palacios, 2001 cited by Etter et al., 2006). Deforestation is related to socioeconomic phenomena and its location depends on geographical, political and economic variables. The expansion of the agricultural frontier in forest areas, as well as extensive cattle ranching, illegal logging and illicit crops (e.g. coca and opium), mining and forest fires have generated large areas of deforestation, endangering the biodiversity of ecosystems.

Furthermore, in Colombia there is no adequate land use, as noted by the DNP (2015), almost 28 percent of Colombian land is overused or underused, mainly in the Andean and Caribbean regions. According to the Ministry of Environment and Sustainable Development (MADS), inadequate land use for agricultural activities has been one of the causal factors of land degradation in Colombia, being responsible for more than 40 percent of degradation (Sylvester et al., 2020). Forests not only contain about 90 percent of terrestrial biodiversity, but also help capture and store carbon, regulate climate, maintain the water cycle, purify water and mitigate natural hazards (Garcia, 2014). Colombia has 59.7 million hectares of natural forest, of which 171,685 hectares were deforested in 2020, 8 percent more than the previous year. The highest deforestation is in the Amazon region with 63.7 percent, followed by the Andean region with 16.9 percent (IDEAM, 2021).

4.1.1.1.2 Water use

Colombia continues to be a country rich in water resources, with several rivers and lakes throughout its territory (FAO, 2015b; Camacho Botero, 2020). The available water supply is 1,214,258 million m^3/year, which represents a per capita total of 28,370 m^3 of water, considered a country of high-water availability (IDEAM, 2019 cited by Government of Colombia, 2019). Nonetheless, water resources in Colombia are limited and the country faces significant scarcity problems, especially in the dry season in the Caribbean region (FAO, 2015b). In fact, 35 percent of the country's population resides in areas with moderate to high water stress, making people and businesses in these areas vulnerable to water scarcity (IDEAM 2018 cited by Government of Colombia, 2019). Likewise, not only the quantity of water in a country should be considered, but also its quality; in Colombia there are severe water pollution problems, which limit its availability for uses such as drinking water purification or agricultural irrigation, generating adverse impacts on the environment and negative consequences on public health (Camacho Botero, 2020).

According to the IDEAM (2019), the main water-consuming economic sector is agriculture with 43.1 percent, followed by energy with 24.3 percent and livestock with 8.2 percent, concentrating 76 percent of the national water demand (Government of Colombia, 2019). Figure 4 shows the country's internal renewable freshwater resources (internal river flows and groundwater from rainfall) from 2000 to 2019, which demonstrate a decrease over the 20 years from 54,698.26 m^3/year in 2000 to 42,739.8 m^3/year in 2019 (World Bank, 2021a).

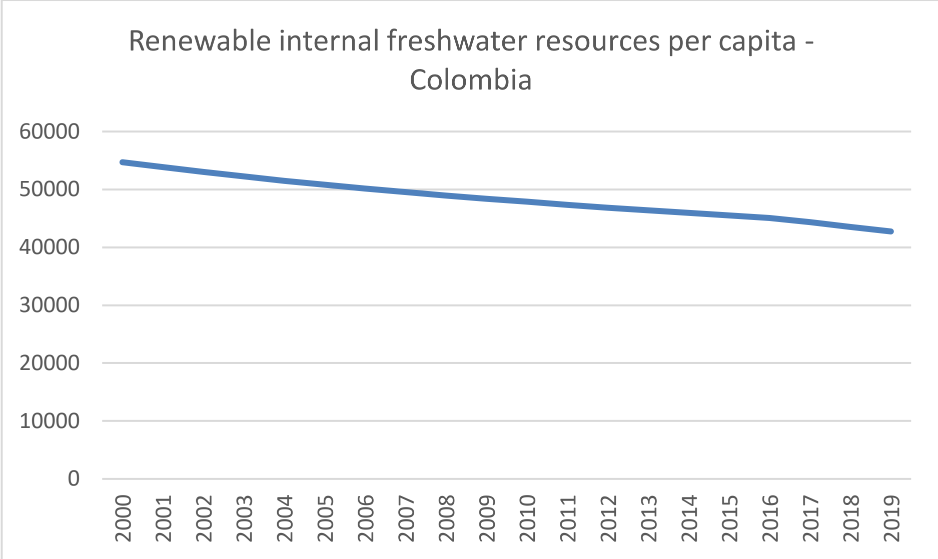

FIGURE 4: RENEWABLE INTERNAL FRESHWATER RESOURCES PER CAPITA IN COLOMBIA

Source: World Bank, 2021a

Colombia is also lagging behind in irrigation and drainage coverage; of 18.4 million hectares that can potentially be developed with this service, only 1.1 million hectares have it, i.e., a coverage of 6 percent (DNP, 2019). In addition, there is a salinization process in medium- and large-scale public irrigation districts, a problem that has worsened due to the lack of drainage infrastructure and surface irrigation management (FAO, 2015b). Figure 5 shows total water withdrawals for agriculture in Colombia between 2000 and 2019, only agriculture accounts for about 74 percent of total water withdrawals, with irrigation being the main water use (World Bank, 2021a).

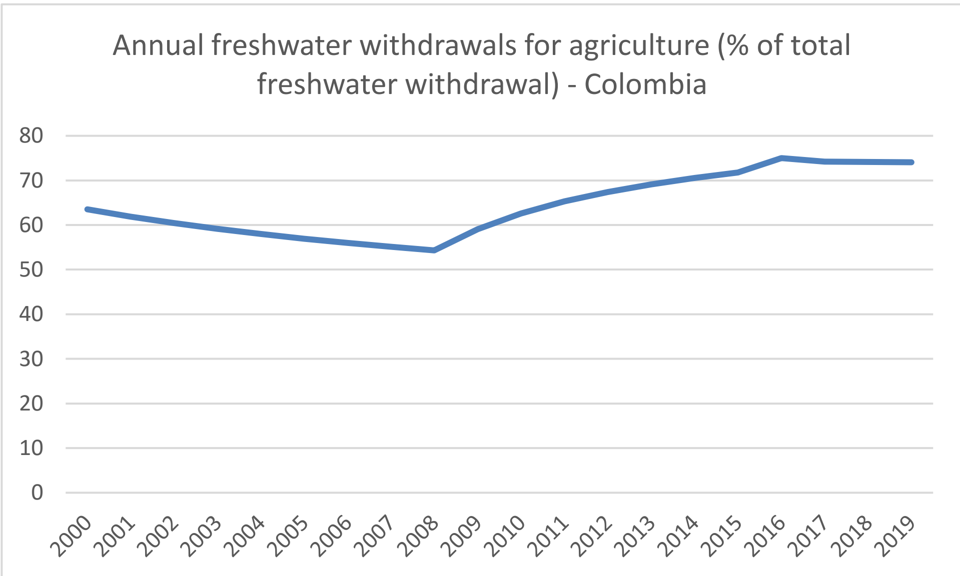

FIGURE 5: ANNUAL FRESHWATER WITHDRAWALS FOR AGRICULTURE (% OF TOTAL FRESHWATER WITHDRAWAL) IN COLOMBIA

Source: World Bank, 2021a

4.1.1.2 Food loss

Colombia has studies on FLW conducted by the Ministry of Health and FAO in 2012, by two Colombian institutions, the National Federation of Merchants (FENALCO) and the Consumer Research Center (CICO) in 2015 and by the National Planning Department in 2016 (DPN, 2016).

According to the latter study, which compiles information from the other two and complements them, in the country the supply of food available for human consumption is 28.5 million tons per year (FAO, 2014 cited by DNP, 2016). However, not all of it is consumed due to FLW throughout the supply chain. Of the total food available, 34 percent (9.76 million tons) is lost, of which 40.5 percent (3.95 million tons) is lost in agricultural production, 19.8 percent (1.93 million tons) in post-harvest processing and 3.5 percent (342,000 tons) in industrial processing processes, accounting for 64 percent of food losses in the country (DNP, 2016). In terms of products lost, 62 percent corresponds to fruits and vegetables, 25 percent to roots and tubers and 8 percent to cereals (DNP, 2016). At the regional level, the highest level of loss occurs in the Andean region with 27.7 percent, especially in Cundinamarca, Santander, Norte de Santander and Boyacá, followed by the Caribbean region with 18.2 percent and the Pacific region with 17.1 percent (DPN, 2016).

4.1.2 Rice production

Rice is the country's third most important crop after coffee and maize, and plays a major role in the country's food security and rural consumption (Van Brackel et al., 2021). Manual rainfed rice was the first type of rice introduced in Colombia since the arrival of the Spaniards and was the main type of production until the 1920's, and from 1930 onwards, rice began to be cultivated in irrigated and mechanized rainfed systems (Rosero, 1992).

In 1948, the National Federation of Rice Producers (FEDEARROZ) was founded as a national trade association, whose purpose is to defend the common interests of its members (Beintema et al., 2006; Van Brackel et al., 2021). This was followed by the establishment of the National Rice Fund (FNA) in 1984, which determined the application of the fund's resources in research, technology transfer and marketing programmes (Van Brackel et al., 2021).

Subsequently, the Climate Service was created in 2007 by FEDEARROZ-FNA due to the dependence on specific environmental conditions for the development and growth of the crop (Rojas et al., 2018). The project provides environmental information – mainly meteorological – to understand the behaviour of the crop given the climatic conditions at a specific moment. This led to the creation of an Android application called "*Planea tu cultivo*" (Plan your crop), where different monitoring information, climate prediction and yield forecasts can be reviewed (Rojas et al., 2018). Moreover, the Massive Technology Adoption Programme (AMTEC) was created in 2012 as a model for improving crop agronomic practices through technology transfer, increasing crop yields and reducing direct production costs, and the programme also includes training and capacity building of farmers (Van Brackel et al., 2021; Lacambra et al., 2020).

The production of rice is comprised of 16,403 farmers, of which 70 percent produce on less than 10 hectares, 25 percent between 10 – 50 hectares, 6 percent between 50 – 200 hectares, and 1 percent on more than 200 hectares (Van Brackel et al., 2021; Lacambra et al., 2020). Additionally, 61 percent of the producers are tenant farmers, so they change lots every season (Van Brackel et al., 2021).

Colombia has five major rice production zones: Central, Llanos, Costa Norte, Bajo Cauca and Santanderes, and three types of production: manual drying, mechanized drying and irrigation. Manual rice cultivation represents approximately 1 percent of the country's production destined for self-consumption (Van Brackel et al., 202). The irrigation system is found in the regions Central, Costa Norte and Santanderes, and the mechanized rainfed system in Los Llanos and Bajo Cauca (Van Brackel et al., 2021). In terms of production, in the early 2000s, 70.4 percent was obtained in irrigated systems and 28.2 percent in mechanized rainfed production, but in 2020 production changed and now 50.1 percent is produced in irrigated systems and 48.9 percent in mechanized rainfed systems (FEDEARROZ, 2021).

The most cultivated areas are Casanare and Meta located in the region of Los Llanos with 27.6 percent and 13.5 percent respectively, Tolima and Huila placed in the Central region with 18.2 percent and 6.7 percent respectively, Sucre situated in the region of Costa Norte with 8.3 percent and Norte de Santander positioned in the Santanderes region with 6.1 percent, only these departments accumulate 80.5 percent of the total cultivated area in the country (IV CNA, 2016 cited by FEDEARROZ, 2021). In fact, producers cultivating on less than 50 hectares account for 93 percent of the farmers and produce 46 percent of the rice, while the remaining 7 percent are responsible for the other half of the production (Van Brackel et al., 2021).

Figure 6 shows the harvested area in hectares, production in tons and yield in hectogram per hectare (hg/ha) of rice production in Colombia between 2000 and 2021, the figures for which are shown in Appendix 1. The harvested area has averaged 502,967.86 hectares over the twenty-one years; however, there has been a drop in production in different years, with the greatest impact in 2002, from 2005 to 2008, 2010 and 2014; after 2016 there has been an increase in harvested area of more than 520,000 hectares.

Regarding production in tons, on average it has been 2,482,720.91 tons, with a similar trend to the harvested area with some drops in 2002, 2006, 2010 and 2013. As for the yield, the average has been 49,091.59 hg/ha, however, it dropped considerably in 2010 with 41,233.00 and in 2013 with 38,371.00, from 2014 it has increased from 47,836.00 to reach 61,078.00 in 2021. According to FEDEARROZ (2021), part of the decreasing trend between 2008 and 2011 was caused by climate variability generated by global warming and the lack of rice varieties that could withstand extreme climates.

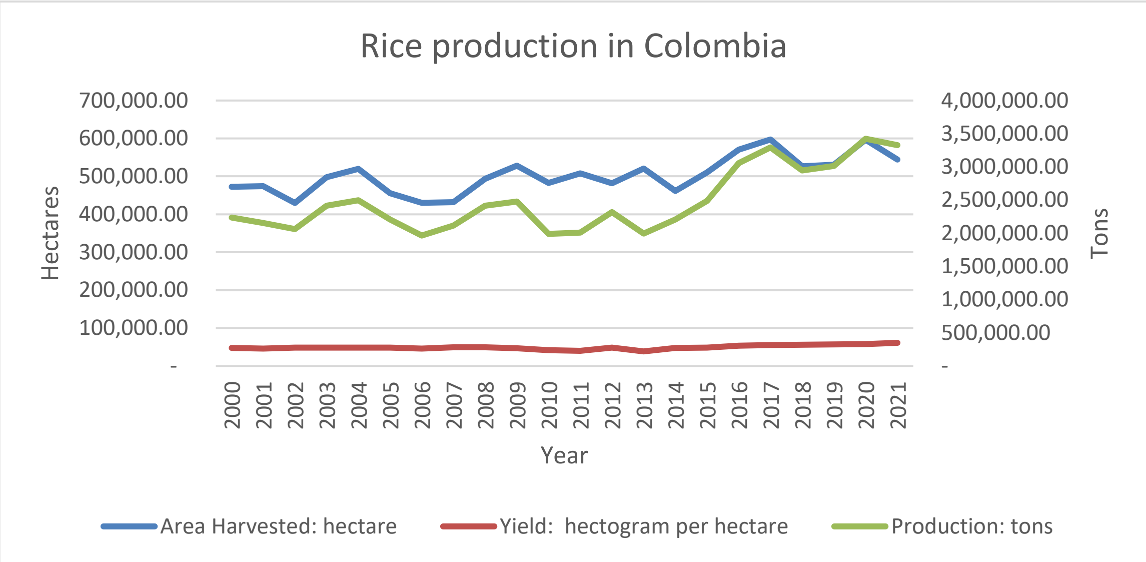

FIGURE 6: RICE PRODUCTION IN COLOMBIA

Source: Adapted from FAO, 2022a

4.1.2.1 Sustainable agricultural practices

The sustainable agricultural practices presented in this section come from the documentary analysis described in the methodology and summarized in Appendix 3, which shows where in the agricultural process it is implemented, in what region, to address what problem and how it is impacting economically, socially and environmentally. This section explains the practices and their benefits in depth.

The introduction of sustainable agricultural practices in rice production began in 2002 in Colombia with biofertilizers. These promote plant nutrition and growth by facilitating the availability of nutrients such as nitrogen, phosphorus and/or water in the crop. In the case of rice, high amounts of these components (mainly nitrogen, phosphorus and potassium) are required for its nutrition, but they are of low efficiency in tropical agriculture (Sanjuán Pinilla & Moreno Sarmiento, 2010). Therefore, it is important to obtain these components in additional products such as biofertilizers. The benefits of biofertilizers over chemical fertilizers are lower production costs leading to higher productivity, less dependence on chemical fertilizers and lower environmental impact (Sanjuán Pinilla & Moreno Sarmiento, 2010; Castilla Lozano & Tirado Ospina, 2022). However, a good technical criterion with microbiological soil analysis is indispensable so that the use of biofertilizers is applied efficiently and does not become an additional expense (Castilla Lozano & Tirado Ospina, 2022).

In 2010, the System of Rice Intensification (SRI) was implemented in the rice sector. The SRI is a system intended for small and medium farmers, which applies agroecology and microbiology techniques for efficient water use (Acosta Buitrago, 2011). It is applied in organic rice production, reducing water consumption and improving yields, nonetheless, the system requires a high level of manual labor or specialized machinery to expedite the work (Acosta Buitrago, 2011; Witkoski, 2017). Hence, in the case of Colombia it was only used for five years in the Tolima region.

Two sustainable practices, crop rotation and the use of residues and compost to fertilize crops, were incorporated in 2012. Crop rotation emerged as a response to the Free Trade Agreement (FTA) signed with the United States, due to the potential decrease in rice prices caused by the introduction of international competition in the national market, which opened up the possibility for crop rotation with crops that were previously unattractive compared to the profitability of rice, such as maize, soybean and cotton (FEDEARROZ, 2012). The benefits of using this technique are flexibility in sowing times, reduced production costs and water use per hectare, and improved defense against weeds (FEDEARROZ, 2012).

The second technique is to use crop residues and nutrient recycling for fertilization and crop nutrition (Castilla Lozano, 2012). The benefits of this technique are to increase the amount of carbon and potassium in the rice crop which increases rice yields, increase profitability while conserving natural resources, and decrease chemical pollution and GHG emissions (Castilla Lozano, 2012). The process consists the use of rice chaff in combination with compost and the application of fungi (such as Trichoderma), leaving it to act for approximately one week and then planting (Castilla Lozano, 2012).

In 2014, a stakeholder project was launched, in which scientists from the CIAT-based Climate Change, Agriculture and Food Research Program (CCAFS) conducted an analysis of huge data sets - mainly on crop and climatic conditions in the rice sector - to understand the impact of climate variations on rice yields (CCAFS, 2016). Following the research, the findings were reported to FEDEARROZ to advise rice farmers that it was better not to plant at all in a specific region of the country because a drought was coming. This prevented 170 farmers from losing their harvest (CCAFS, 2016)

In 2016, two sustainable practices were implemented in the rice sector, Alternative Wetting and Drying (AWD) and recommended rates of fertilizers. AWD is a climate-smart agriculture management approach that improves water management through an intermittent irrigation program that alternates between flooded and non-flooded conditions (Chirinda et al., 2017). The benefits of this technique are reduced methane (CH4) emissions, reduced of water inputs and reduced irrigation costs (Chirinda et al., 2017; Chirinda et al., 2018). Nevertheless, farmers have not applied it due to lack of enabling policy environment, inadequate water infrastructure and lack of awareness of the technique and its benefits (Chirinda et al., 2018).

The second technique is the implementation of recommended rates of fertilizers. Soil care is essential to increase rice yields, so it is necessary to make decisions with tailor-made solutions for each rice-growing region of the country according to its own geographic and agro-climatic conditions (Castilla Lozano et al., 2018). The benefits are increased nutritional efficiency, reduced chemicals in the soil and reduced production costs.

4.1.2.2 Digital agricultural technologies

The digital agricultural technologies presented in this section come from the documentary analysis described in the methodology and summarized in Appendix 5, which shows in which part of the agricultural process it is applied, in which region, to address which problem, and what solution it presents. The section below explains the technologies in more detail and their advantages.

The main introduction of technologies in the rice sector occurred in 2012 in Colombia with the objective of improving rice yields, and are divided according to the stage at which they are implemented: land preparation, planting and irrigation system (Alwarritzi et al., 2020). In land preparation, one of the main concerns during crop production is water management, as it plays a key role in fertilization efficiency because according to soil moisture the nutrient uptake is better. Therefore, two instruments have been implemented to measure and quantify the amount of water entering the rice field, one tool is a Baro-Diver used as a data logger and eTape which is a liquid level sensor (Castilla Lozano & Tirado Ospina, 2022).

Another issue is making decisions on the amount of fertilizer to be applied to the crop, which is usually done with a visual observation when the crop is chlorotic, which generates losses in the production potential of the variety planted (Castilla Lozano & Tirado Ospina, 2022). For this reason, instruments such as Chlorophyllometer or the Soil Plant Analysis Development (SPAD) are used to determine the appropriate times for fertilizer application, especially nitrogen (Castilla Lozano & Tirado Ospina, 2022). These are tools that estimate the chlorophyll and nitrogen content in the leaves of different crops indirectly, quickly and without tissue destruction.

Furthermore, due to constant soil changes caused by climate and agricultural practices, as well as inadequate water management in hard-to-reach areas, three technologies were implemented: vibratory chisel plows, ground plane levelers and tapia (Alwarritzi et al., 2020; Pineda Suarez, 2021; DANE & FEDEARROZ, 2018; Guzmán García et al., 2018). The first to improve water infiltration in compacted soils by allowing a deep tillage operation and breaking up hard layers while leaving the top layer (Alwarritzi et al., 2020; Pineda Suarez, 2021; Guzmán García et al., 2018), which improves soil structure while tilling one seedbed at a time (Alwarritzi et al., 2020). The second instrument is used connected to the tractor, to eliminate – in a superficial way – the irregularities and unevenness of the soil caused by the previous production (Alwarritzi et al., 2020; Pineda Suarez, 2021; Guzmán García et al., 2018), whose objective is to increase efficiency in downstream works, such as reducing runoff water losses (Pineda Suarez, 2021).

The latter is also connected to the tractor, and is used to build the ridges that divide the lot into plots and retain water for crop development (Alwarritzi et al., 2020; Pineda Suarez, 2021; Guzman Garcia et al., 2018). It improves the efficiency of water distribution in the rice field (Pineda Suarez, 2021), while allowing farmers to use dry seeding equipment to plant directly over the entire plot, including the top of ridges, preserving the spatial regularity of rice growth (Alwarritzi et al., 2020).The last tool used in land preparation is pre-fertilization, which consists in the application of basal fertilizers to know the soil physiology and be able to manage weeds in a timely manner (Alwarritzi et al., 2020).

In sowing, the techniques used are certified seeds, to avoid germination problems that decrease yield; drill sowing for weed control and for the application of agrochemicals with ground equipment, by direct sowing of dry seeds; and sowing density lower than 150 kg/ha, to obtain a good crop yield, which depends on the optimum plant population, referring to the minimum number of plants per unit area that guarantees a high yield (Alwarritzi et al., 2020). Regarding irrigation systems, the only technique is continuous irrigation, in which water is applied intermittently at intervals of three to five days at the top of the plot until filling the end of the plot, with the objective of controlling the application of water, mainly after applying fertilizers.

In 2014, digital technologies began to be implemented in Colombia. As an example, the CCAFS team developed a mobile phone application for rice farmers to record and disseminate information about their cultivation practices, and also used big data analysis to assess the impact of climate change on rice yields providing recommendations to farmers (CCAFS, 2016; Gil, 2016). That same year, a digital platform was created to assists rice farmers by providing personalized recommendations on fertilizers to be applied to the crop according to the requirements of each place, considering geographical location and history, since it stores geo-referenced information of the lots (Castilla Lozano & Tirado Ospina, 2022; Castilla Lozano et al., 2018).

In 2015, an integrated system was developed for the remote control of electrically pumped irrigation systems, which sends real-time information to the end user via the Internet through a website (Quintero et al., 2016). The system sends notifications about any event occurring in the irrigation system to avoid putting the crop at risk (Quintero et al., 2016).

Additionally, three technologies were implemented in 2016. The first is a Time Domain Reflectometry (TDR) to perform a water monitoring of the lot, which roughly estimates the speed of water propagation in the soil and allows identifying areas with higher and lower moisture retention (Castilla Lozano & Tirado Ospina, 2022; Pineda, 2016; Ortiz Londoño et al., 2020). With the information collected, soil moisture maps are made to prioritize zones or areas that are difficult to access for irrigation (Pineda Suárez, 2021; Castilla Lozano & Tirado Ospina, 2022).

The second is Digital Soil Mapping (DSM), which provides accurate, site-specific information that guides management and technology decisions to increase resource use efficiency and conservation by combining available data and less intensive field sampling to create cost-effective, high-resolution soil maps (Chirinda et al., 2017). The last one is a web management system called *SI-FAweb*, which is a rice fertilization platform used as a support tool that gathers all the necessary instruments for the control and good management of soil fertilization, generating personalized fertilization recommendations to farmers (Castilla Lozano et al., 2018).

In 2017, three new technologies were applied in the rice sector. The first is the Multiple Inlet Rice Irrigation (MIRI), which is part of the precision irrigation that directs the water in a targeted manner (Castilla Lozano & Tirado Ospina, 2022; Pineda Suarez, 2021). It is a system of conduction and distribution of irrigation water through multiple intakes, which are inserted along the hose regulating the water flow through its manual opening and closing system (Guzmán C. et al., 2018).

This system helps to save water, increase irrigation efficiency, reduce crop flooding time, and reduce water arrival time to more isolated areas (Pineda, 2016; Guzmán C. et al., 2018). The second is the Real Time Kinematic (RTK), which is a tool that allows real-time digital elevation mapping for irrigation designs with a high degree of accuracy based on the topography of the terrain (Guzmán C. et al., 2018). The last is a mobile application called *Planea tu cultivo*, which provides rice farmers better information for crop planning throughout the year, including real-time weather information and crop information that is collected and analyzed, indicating the best time to plant (Popescu, 2017).

In 2019, another digital platform was implemented, it is called *¿Va a llover?,* it is a climate service platform that constantly monitors the climate, providing historical average weather conditions, agro-climatic forecasts and real-time weather conditions in the area where planting takes place, which helps determine the amount of nutrients needed by the crop (Castilla Lozano & Tirado Ospina, 2022).

Moreover, four technologies from precision agriculture were implemented in 2020, satellite images by the Normalized Vegetation Index (NDVI), sensors and Global Positioning System (GPS) installed on the harvester, drones and sowing monitors. NDVI is used to optimize fertilizer use through site-specific nutrient application with an index that estimates the quantity, quality and development of the vegetation. (Castilla Lozano & Tirado Ospina, 2022). It is a mapping tool that analyzes historical information from satellite images, where the temporal and spatial variability of the terrain is determined and divided by lots (Castilla Lozano & Tirado Ospina, 2022; Ortiz Londoño et al., 2020; Guzmán C. et al., 2018).

Sensors are used in land preparation, sowing, crop management (e.g., fertilizer application) and harvesting, it is an internal or external device that performs simple measurements such as weather conditions and more complex measurements such as calculating the amount of product applied in a given time and space, and GPS are used to locate the data collected from the sensors and obtain accurate site information (Guzmán C. et al., 2018). Both products generate a yield monitor with software that receives and compiles the information obtained to map soil moisture and yield difference between plots (Guzmán C. et al., 2018; Ortiz Londoño et al., 2020).

Drones are unmanned aerial electronic devices equipped with GPS, sensors, high resolution cameras and radar control to provide information about the state of a terrain, including moisture conditions, temperature and plant behavior during its growth cycle, and even be equipped with NDVI for better crop monitoring showing what the human eye cannot see (Castilla Lozano &

Tirado Ospina, 2022; Guzmán C. et al., 2018). On the other hand, sowing monitors are used to define the amount of seed to be spread in a specific region by combining different aspects that result in a seeding map with the amount of seed supplied at each reference point (Guzmán C. et al., 2018). Finally, in 2022, another digital platform called *Mi registro rural* was created*,* this is a digital citizen service that increased efficiency in the management of documentation, reducing document processing cycles and improving immediate communication of projects, programs and incentives offered to farmers by sector entities (FEDEARROZ, 2022).

4.2 The agricultural sector in Kenya

Kenya is characterized by a great diversity of landscapes home to a rich biodiversity, including savanna grasslands and woodlands, tropical rainforest and semi-desert environments (Mohajan, 2014). It is located on the East African coast with a total land area of 580,370 km² (FAO, 2015a), a coastline of 536 km and water bodies of 11,230 km² (Mohajan, 2014), of which 45.5 percent of the land area is devoted to agriculture and 6.3 percent to forestry (World Bank, 2021b). One of the main features of the country is the Great Rift Valley, which divides the central highlands (FAO, 2015a). The country is divided into 47 counties created by the new Constitution of Kenya in 2010, the old division comprising 8 provinces, Central (11,449 km²), Coast (79,686. 1 km²), Eastern (140,698.6 km²), Nairobi (696.1 km²), North Eastern (127,358.5 km²), Nyanza (12,477.1 km²), Rift Valley (182,505.1 km²), and Western (7,400.4 km²) [Mohajan, 2014].

Due to its location on the equator, the country's temperature varies with altitude above sea level influenced by the intertropical convergence zone, with a wide range of altitudes from sea level in the Indian Ocean to the top of Mount Kenya, which is 5,199 meters above sea level (0 - 5199m) [FAO, 2015, p. 1]. The average annual rainfall is 630 mm, being less than 200 mm in northern Kenya to over 1800 mm on the slopes of Mount Kenya, having a bimodal distribution of rainfall - long rains from March to May and short rains from October to December (FAO, 2015, p. 3).

Agriculture is the backbone of Kenya’s economy, its GDP in dollars is 110.35 billion (World Bank, 2021b, of which 34 percent is in the agricultural sector (WFP, 2022b), however, there is an additional indirect contribution of approximately 27 percent in connection with other sectors (Bhunu et al., 2019). In the Sub-Saharan African region, it is the fourth largest economy (Mohajan, 2014) considered one of the most developed and diversified agriculture-based economies (Kimemia and

Oyare, 2006). The country's main crops are sugarcane, raw beef milk, maize, tea leaves, potatoes and bananas. However, there has been an increase in cereal and legume crops due to food demand and population growth (World Bank; CIAT 2015). In cereals, the main crops are maize, wheat, rice, sorghum and millet (Kogo et al., 2020)

Approximately 59 percent of the country's soils have moderate to high natural fertility, making them ideal for growing a wide range of crops (Musa, & Odera, 2015). However, Kenya's agricultural production is highly dependent on rainfall and vulnerable to changes in weather patterns (AfDB, 2023). Currently, staple food commodities are in deficit (e.g., maize, rice, Irish potato, beef, dairy, and poultry) due to low rainfall (AfDB, 2023). Only 17 percent of the total land is suitable for rain-fed agriculture, while forests cover 2.2 percent of arable land and grasslands and savannah grasslands 82 percent in arid and semi-arid areas (ASALs) [Musa, & Odera, 2015].

Productivity is hampered because only 17 percent of the country gets more than 800 mm of rainfall per year, which is considered the minimum requirement for rainfed agriculture (Musa, & Odera, 2015). At the same time, Kenya has 2.9 million hectares with potential for irrigated agriculture, but only 192,630 hectares are irrigated (Bhunu et al., 2019). As Mohajan (2014) pointed out, commercial agriculture dominates high-potential arable lands, with cropland occupying 31 percent, pasture 30 percent, forest 22 percent and the rest is used for urban infrastructure (Mohajan, 2014). In addition, crops occupy only 60 percent of the high and medium potential land, while permanent crops occupy only 0.97 percent (Mohajan, 2014).

According to World Bank data from 2021, Kenya has a population of 53,005,614 (World Bank, 2021b), with a population density of 93.1 (inhabitants/km2) [Our World in Data, 2023b], of which 72 percent live in rural areas (World Bank, 2021a). Of these, 12.9 million are employed in agriculture (Our World in Data, 2023b), accounting for 54 percent of total formal employment (World Bank, 2021). According to the Human Development Index, the country has a score of 0.60 (Economist Impact, 2023), ranking 143th out of 189 countries in 2019 (WFP, 2022b), where inequality is high, with a Gini index of 0.59 (World Bank, 2021b) and informal employment is about 77 percent, according to national studies (Murunga et al., 2021). Almost 90 percent of the population lives on less than 20 percent of the country's total land area, as the population is concentrated on medium to high potential agricultural land (FAO, 2015).

Agriculture in the country employs 75 percent of the total national labor force (Otieno Onyalo, 2019), where women play an important role accounting for approximately 50.3 percent (FAO 2018 cited by Bhunu et al., 2019). Smallholder production, on the other hand, accounts for 78 percent of total agricultural production (Birch, 2018), being a rain-fed farming practice between 0.2 to 3 hectares of land (Kogo et al., 2020); within smallholder farmers, 70 percent are women (Kledal et al., 2010).

Kenya is one of the most highly educated countries in Africa, with abundant trained human resources that can develop new technologies and create and expand agribusinesses (Mohajan, 2014). At the same time, according to projections, "sub-Saharan Africa is the only region in the world where the rural population will continue to grow beyond 2050" (Jayne et al, 2017, p. 3 cited by Birch, 2018), however, land distribution is becoming increasingly concentrated in the country, generating potential agricultural growth associated with increased inequality (Birch, 2018).

As reported by the Famine Early Warning System Network (FEWS NET), the main causes of food insecurity in Kenya are the effects of drought on crop and livestock production seasons and high inflation, at the same time, stagnant wages in urban areas and declining income earning opportunities in rural areas limit access to food for poor households (FEWS NET, 2022). According to the WFP hunger map, 19 million people have insufficient food consumption and 12.7 percent of children under 5 years of age are chronically undernourished (WFP, 2023).

4.2.1 Development of the agricultural sector

In Kenya, the dynamics of state creation, economic growth, and electoral politics are heavily influenced by land politics (Boone et al., 2021). Agriculture played an important role in the history of Kenya's liberation from British colonizers, in which a conflict over land served as a key political motivation (Kariuki, 2009). It was a struggle of rights over ownership, control, access and use of land (Kariuki, 2009). Kenya traditionally had an open frontier where they shared land as the population increased (Leo, 1978), but when Europeans came to the country, they took over large plots of land, letting Kenyans work in exchange for cash wages; but as cash agriculture progressed, restrictions on the use of the land and Kenyans' work on it began, leading to a decline in their standard of living and impoverishment (Leo, 1978). Thus, in the 1940s and 1950s, the Kenyan anti-colonial movement emerged to reclaim the territory that the colonial government had alienated (Boone et al., 2021).

From the 1950 to 1953, the Mau Mau rebellion exploded due to the growing rural frustration, it was a guerilla group that battled British colonizers to reclaim their seized territory (Kariuki, 2009). To quell the uprising, the British government quickly devised a land reform scheme - the Swynnerton plan in 1954 (Kariuki, 2009), which was intended to boost colonial production of goods and raw materials through state intervention (Thurston, 1987). Between 1956 and 1960, the country underwent a program of land tenure reform and intensive development never before attempted in a British African territory (Thurston, 1987). This had two main components, the lifting of colonial legal restrictions on access to land and the large-scale introduction of cash crops (Thurston, 1987; Kariuki, 2009). The objective was to create a class of cumulative peasants established in economic units, through a process of consolidation and registration of land as freehold property (Kariuki, 2009), but the economic success and growth envisioned in this program never materialized.

In 1962 the Million Acres Scheme was created, it was one of the smallholder settlement programs that were crucial to Kenya's transition to independence, this scheme helped to de-racialize land ownership and offer it to people displaced in the 1950s by struggles against British colonial rule (Boone et al., 2021). The goal of the initiative was to transfer 1.2 million acres of large-scale farms and ranches formerly owned by Europeans to African smallholder farmers (Leo, 1978). A land market was created for white settlers to sell their agricultural properties protecting their interests and supporting the value of the land for those who wanted to stay (Boone et al., 2021).

After the independence of Kenya in 1963, domestic policy strategy was influenced by the green revolution, through donor-driven programs aimed at increasing the use of modern agricultural inputs in low- and middle-income countries (Mann & Iazzolino, 2021). In the 1960s and 1970s, there was strong growth and high savings that helped break the colonial economy, however, pricing structures favored industry over agriculture and favored larger cash crop producers over smallholder subsistence farmers (Mann & Iazzolino, 2021). In addition, between the 1970s and 1980s, Kenya's agriculture faced challenges due to the global economic downturn and declining commodity prices. The Kenyan economy was impacted by several external shocks affecting the balance of payments and food prices, such as the oil price hike in 1973, the drought in 1980 and a fall in export prices in 1982 (Mann & Iazzolino, 2021).

In 1980, Kenya signed the first Structural Agreement Loan with the World Bank, with which the government agreed to more liberal trade and interest rate regimes, as well as an outward-oriented industrial policy (Gertz, 2008). The agricultural sector had an average annual growth rate of 3.5 percent between 1980 and 1990 (Government of Kenya, 2010). In the 1990s, the private sector imported and distributed most fertilizer, but the government continued to purchase and distribute significant amounts through subsidy programs (Birch, 2018). However, due to low investment in the sector, poor management and lack of attention to agricultural extension and research, growth slowed to 1.3 percent (Government of Kenya, 2010).

Since the mid-2000s, a coalition of different actors arose with the objective of encouraging a new Green Revolution through the application of new technologies, mainly focused on certified seeds and fertilizers, supplied by the public and private sectors (Odame & Muangue, 2011). Growth began to increase in the first half of 2000 with an average growth rate of up to 2.4 percent (Government of Kenya, 2010). In 2003, the goal in Kenya was to rebuild its rural market and increase financing for smallholder farmers with the help of the private and philanthropic sector, creating a suitable environment for digital entrepreneurs and making Nairobi the site of numerous entrepreneurship training programs and business start-up competitions (Mann & Iazzolino, 2021). The government identified the agricultural sector as a priority for economic growth and increased investment in the sector, allocating an average of 4.5 percent of the national budget to it (Government of Kenya, 2010).

However, in 2008, the agricultural sector experienced a negative 2.5 percent due to the crisis caused by escalating global food and fuel prices and financial crises (Government of Kenya, 2010). According to Birch (2018), public spending on agricultural research as a percentage of GDP gradually declined over the last decade, being 0.48 percent in 2016, considered about one-third of what it was in 2006 (Birch, 2018). Kenya faces different challenges such as "poverty, inequality, climate change, debt sustainability, corruption and economic vulnerability to internal and external shocks" (Bhunu et al., 2019, p.1). At the same time, Kenya's economy depends on the agricultural sector, which is the most negatively affected by climate change due to the deterioration of natural resources (Bhunu et al., 2019).

On the other hand, since 2009, the innovation ecosystem in Kenya has grown driving the expansion of technology start-ups in the country by providing a space and infrastructure for developers, mentorship from experienced entrepreneurs and networking opportunities with investors, other developers and business partners (Baumüller, 2016). According to a report by Tsan et al., (2019), there are 64 digital solutions in the market originating in Kenya and 114 additional digital solutions with a presence in the country, addressing topics such as advisory services, market lineage, supply chain management, financial access and macro-agricultural intelligence. It is an entrepreneurial growth ecosystem that has attracted investors and donors from different countries, such as angel investors – eager to support emerging talents and ideas, as well as funds and different competitions (Baumüller, 2016), making Kenya a hotspot for the creation of agricultural applications (Krishnen et al., 2020). The growth prospects for this market in the country are promising, as continued private investments and donor support are expected, as well as an increase in digital literacy in Kenya (Tsan et al. 2019).

4.2.1.1 Impact of agriculture on the environment

Population growth and extreme climate changes in Kenya have increased the pressure on agriculture to provide food for its entire population and also the demand for ecosystem services (Ministry of Environment and Natural Resources, 2016; Mulinge et al., 2016), leading to land use changes that transform land cover into croplands, pastures and human settlements generating deforestation, biodiversity loss and land degradation (Maitima et al., 2009). The replacement of forests, wetlands, savannas and other native landscapes poses a serious threat to the environment's ability to sustain food production, maintain freshwater and provide other ecosystem services (Maeda et al., 2010).

Extreme weather events cause more than 70 percent of natural disasters in Kenya, although the country has experienced periodic droughts throughout its documented history, their magnitude and severity have recently increased (Ministry of Environment and Natural Resources, 2016). Kenya is expected to suffer significant consequences of climate change, such as an increase in average temperature and rainfall (Bryan et al., 2013), which negatively affects agricultural production, access to food and stability of food supply (Maeda et al., 2010). The country is particularly vulnerable to climate change due to its limited capacity to adapt (Bryan et al., 2013).

4.2.1.1.1 Land use

Land degradation in Kenya is a major environmental issue that is primarily caused by human activities such as deforestation, overgrazing, soil erosion, and unsustainable agricultural practices (Mulinge et al., 2016). According to Le et al. (2014), 22 percent of Kenyan land area was degraded between 1982 and 2006, including 31 percent of croplands, 46 percent of forested land, 42 percent of shrub areas, and 18 percent of grasslands (Le et al, 2014 cited by Mulinge et al., 2016, p. 474). The degradation of land in Kenya has led to a decline in soil fertility, water scarcity, loss of biodiversity and food insecurity, which has affected the livelihoods of millions of people who depend on agriculture for their sustenance. This problem has been exacerbated by climate change, which is causing prolonged droughts and extreme weather events that aggravate soil erosion, salinization and land degradation (Ministry of Environment and Natural Resources, 2016). According to IFM (2010), land degradation in the country is estimated to have an annual economic cost of about 3 percent of GDP, a cost that is associated with the impact of climate change, soil erosion, pollution, invasive species and agrochemical toxicity (Mulinge et al., 2016).

Furthermore, deforestation is a significant driver of land degradation in Kenya; forests occupied 10 percent of the total land area when the country gained independence in 1963, but this figure had dropped to about 2 percent by 2003 (Ministry of Environment and Natural Resources, 2016). The loss of forests reduces the ability of the land to absorb and store water, leading to soil erosion and reduced soil fertility. Figure 5 shows the loss of tree cover in Kenya from 2001 to 2021, during this period 368,000 hectares were lost, which is equivalent to a decrease of 11 percent of the total tree cover (Global Market Watch, 2021a). The main causes of deforestation are poor protection, forest clearing for settlements, fuel wood, legal/illegal logging and cultivation of crops (Ministry of Environment and Natural Resources, 2016; Mulinge et al., 2016).

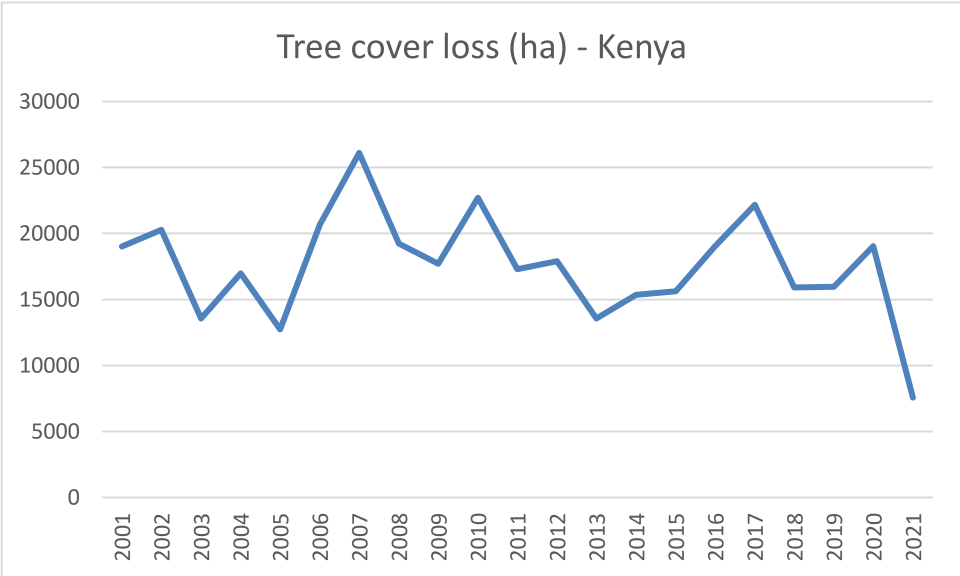

FIGURE 7: TREE COVER LOSS IN KENYA

Source: Global Forest Watch, 2021b

4.2.1.1.2 Water use

Kenya is a drought-prone country where 84 percent of the total land area is arid and semi-arid (Ministry of Environment and Natural Resources, 2016), at the same time, water availability is unevenly distributed, where the Lake Victoria basin contains approximately 56 percent of the country's water resources, which cannot be used for irrigation in remote places (Mohajan, 2014). The country suffers from famine every 3-4 years and is highly vulnerable to the effects of climate change (Bhunu et al., 2019). According to the FAO (2015a, p. 7), “total renewable water resources are 30,700 million m³/year, or 692 m³/year per capita in 2014”. Kenya is classified as water scarce because the threshold is below 1000 m³/year (Bhunu et al., 2019). Figure 7 shows the country's internal renewable freshwater resources (internal river flows and groundwater from rainfall) from 2000 to 2019 (World Bank, 2021b), which demonstrate a decreased over the 20 years from 670.95 m³/year in 2000 to 406.27 m³/year in 2019 (World Bank, 2021b).

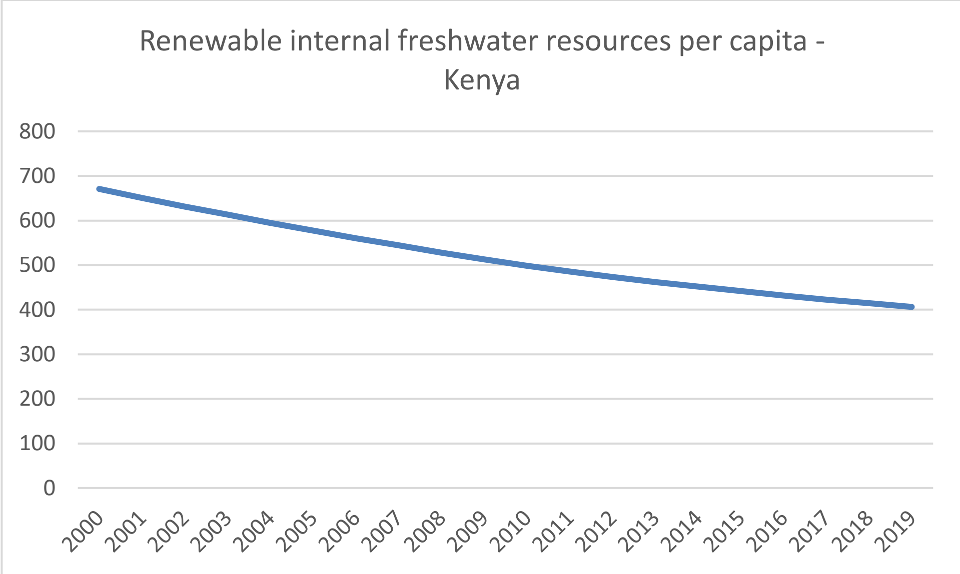

FIGURE 8: RENEWABLE INTERNAL FRESHWATER RESOURCES PER CAPITA IN KENYA

Source: World Bank, 2021b

Moreover, agriculture in Kenya is mainly rain-fed, with only 192,630 hectares under irrigation comprising for 4 percent of the total area (Bhunu et al., 2019). This accounts for about 3 percent of GDP and 18 percent of the total value of agricultural products (Ministry of Environment and Natural Resources, 2016). In addition, 50 percent of total water demand, estimated at over 3.2 billion m³ in 2010, is used for irrigation (FAO, 2015a). Figure 8 shows the total water withdrawals for agriculture in Kenya between 2000 to 2019, only agriculture accounts for about 80 percent of total water withdrawals, with irrigation being the main water use (World Bank, 2021b). On the other hand, the agricultural sector has been affected with salinization on irrigated land, according to Liniger et al., (2011), 30 percent of country's irrigated land is salinized (Mulinge et al., 2016), and over the last century, 27 percent of high-value irrigated land in Kenya has been lost to salinization (Tiffen et al. 1994 cited by Mulinge et al., 2016).

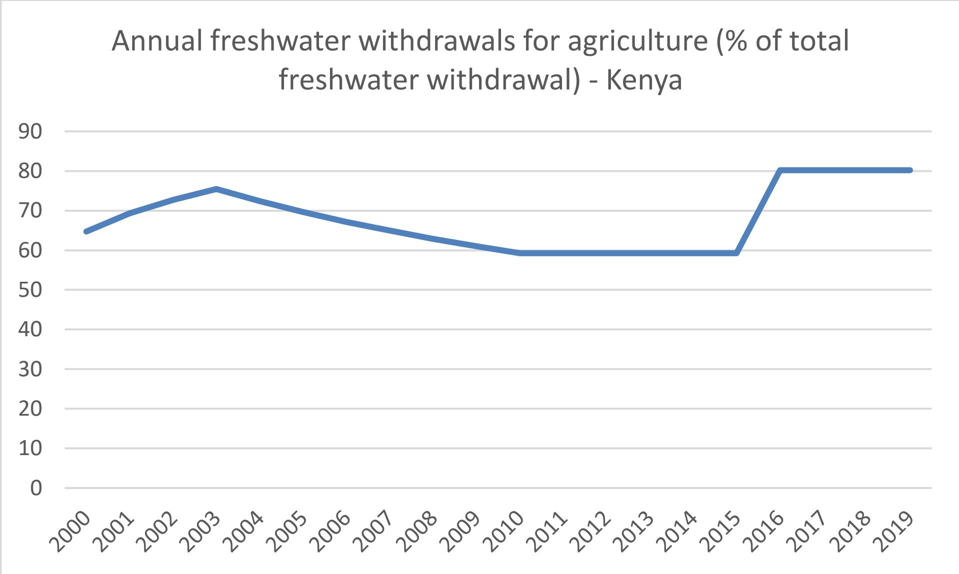

FIGURE 9: ANNUAL FRESHWATER WITHDRAWALS FOR AGRICULTURE (% OF TOTAL FRESHWATER WITHDRAWAL) IN KENYA

Source: World Bank, 2021b

4.2.1.1.3 Food loss

Kenya mainly relies on postharvest loss studies conducted by the African Postharvest Loss Information System (APHLIS), with information from 2000 to 2021. According to APHLIS (2021), harvest and field drying losses are 6.4 percent for maize, 4.6 percent for sorghum, 4.4 percent for rice and 4.4 percent for wheat; in threshing and shelling, losses are 3.6 percent for sorghum, 3.5 percent for wheat, 3.1 percent for rice and 1.3 percent for maize; in winnowing, losses are 2.5 percent in rice.

It is estimated that more than 30 percent of harvested crops are lost along the value chain as a result of poor post-harvest management, insufficient inappropriate storage facilities, and poor product handling (Government of Kenya, 2023). In addition, pests and diseases, as well as unfavorable weather, contribute significantly to food loss in Kenya. Climate change is projected to increase yield losses of 8 to 22 percent for key staple crops such as maize, wheat and rice, due to potential increases in evapotranspiration by 2050 (Bryan et al., 2013). This is a major concern, considering that Kenya still struggles with food insecurity, with millions of people experiencing hunger and malnutrition.

4.2.2 Rice production

Rice is the third most important crop in the country, after wheat and maize, and plays a key role in food security and poverty reduction (Evans et al., 2018). It was introduced by Europeans in 1907 along the Kenyan coast, and under British colonial rule in 1955, irrigated rice cultivation was established in the country (Evans et al., 2018; IRRI, 2018). Between 1966 and 1998, after the country's independence, irrigated rice was under the control of the National Irrigation Board (NIB) established by the Government of Kenya, which then passed into the hands of the farmers. The NIB was created to develop irrigation schemes and rice marketing in the country; the board provided farmers with agricultural inputs and services on credit, while farmers were assigned a quota for their own consumption and were required to give the remainder to the NIB (Evans et al., 2018; Ilie et al., 2022).

In 1989, the African Development Bank (ADB) launched the Western Kenya Rainfed Rice Development Project (WKRRDP), which was implemented by the Lake Basin Development Authority (LBDA) until 2000; the program provided credit to rice farmers, construction of a rice mill, and adaptive research (Evans et al., 2018). In 1992, the African Rice Center (ARC) developed the New Rice for Africa (NERICA) as a process of hybridizing African rice with Asian rice to improve production yields; there were trials in the country in 2004 and four years later the rice cultivars were released to farmers (Evans et al., 2018; IIRI, 2018).

Moreover, from 2007 to 2019, the International Rice Research Institute (IRRI) and ARC created the Stress Tolerant Rice for Africa and South Asia (STRASA) project with the objective of developing and distributing abiotic stress tolerant rice varieties to millions of farmers in rainfed rice-growing environments on both continents (IRRI, 2018). In 2008, the Alliance for a Green Revolution in Africa (AGRA) and the Japan International Cooperation Agency (JICA) launched the Coalition for Africa Rice Development (CARD) initiative, aiming to double rice production in the latter and enable the green revolution to increase productivity in the crop (Evans et al., 2018). Similarly, the National Rice Development Strategy (NRSD) phase 1 from 2008 to 2018 was launched with the objective of doubling rice production. Furthermore, in 2015, the Agricultural Mechanization Research Institute, Agricultural Technology Development Centers and Agricultural Mechanization Services were launched with the objective of promoting the use of effective technology (Ilie et al., 2022).

In 2019, the International Fund for Agricultural Development (IFAD) launched a three-year project in Kenya, Uganda and Madagascar with two institutes for agricultural development in Africa with the objective of improving the performance of local rice value chains in these three countries by combining knowledge and expertise (CGIAR, 2020). This is done through the identification of rice hubs that represent key rice growing environments and market opportunities to implement appropriate rice technologies and innovations to overcome challenges, improve farmer capacity, and strengthen stakeholder support. In Kenya, nine clusters with different rice growing ecologies (irrigated lowland, rainfed lowland, rainfed upland) have been identified to improve rice production and economically empower local communities. Additionally, the national strategy NSDR phase 2 was launched from 2019 to 2030 with the objective of increasing rice production from 112,000 tons in 2018 to 846,000 tons in 2030 (CGIAR, 2020).

Rice consumption is increasing in Kenya at an annual rate of 12 percent, but only about 20 percent of global demand is met by domestic rice production (Evans et al., 2018; Ilie et al., 2022), i.e., according to the Ministry of Agriculture (2008), total national rice production must increase at a rate of 9.3 percent per year to be self-sufficient in rice production by 2030 (Evans et al., 2018).

Rice is mainly grown by approximately 300,000 smallholder farmers in the Central (Mwea), Western (Bunyala), Coastal (Tana delta, Msambweni), and Nyanza (Ahero, West Kano, Migori and Kuria) provinces (IRRI, 2018; Ilie et al., 2022), with two types of production: rainfed and irrigated lowland; where Irrigable ecosystems cover approximately 78 percent of Kenya's total rice-growing area. (Evans et al., 2018).

The integrated large farm chain, the highly concentrated chain based on NIB schemes, and the traditional market value chain based on non-NIB irrigated and rainfed output are the three main value chains in the rice subsector (Evans et al., 2018, p. 65).The NIB's national irrigated schemes are Ahero, Bunyala, Bura, Hola, Mwea, Perkerra and West Kano (Evans et al., 2018), with Mwea being Kenya's main rice-producing region, accounting for 80 percent of the total production (Ilie et al., 2022, p. 12).

Rice is also grown in small amounts along river valleys, particular(ly in smallholder irrigation schemes such as Kore, Alungo, Nyachoda, Wanjare, Anyiko, and Gem-Rae in western Kenya and Kipini, Malindi, Shimoni, and Vanga on the coast (Evans et al., 2018). In addition, there is continuous flooding in irrigable ecosystems, as is the case in the Mwea, Ahero, Bunyala and West Kano systems (Evans et al., 2018).

Figure 10 shows the harvested area in hectares, production in tons and yield in hectograms per hectare of rice production in Kenya between 2000 and 2021, the figures for which are shown in Appendix 2. The harvested area has averaged 22,258.41 hectares over the twenty-one years, however, it started with 13,882.00 in 2000 and increased to 31,349.00 in 2013; after 2014 there has been variability with an average of 27,792.38 having 25,548.00 in 2021. As for production in tons, it has averaged 90,125.00 tons, started with 52,349.00 in 20000 until 186,000.00 in 2021, having a sharp decline in 2008 with 21,991.00 and a steady recovery until a slighter drop in 2017 with 81,198.00 tons.

In terms of yield, the average has been 39,238.82 hg/ha, with only 37,710.00 hg/ha in 2000 and with a drop of 13,076.00 hg/ha in 2008, which has steadily recovered to a yield of 72,804.00 hg/ha by 2021. According to Atera et al., (2017), an identified challenge in rice production in Kenya is high post-harvest losses accounting for about 15 to 50 percent of the market value of production, which is also a consequence of lack of drying facilities that generates high production costs, threat to food security and generates less competitive domestic production than imports (Ilie et al., 2022).

The increase in rice production has been made possible through the implementation of the national strategy NRSD Phase 1 and 2, focusing on improving rice production through the use of hybrid seeds, developing water-saving rice cultivation, improving mechanization along the rice value chain, developing the rice seed distribution system, training staff and farmers, building two rice research laboratories, and improving networking (Ministry of Agriculture, Livestock, Fisheries and Cooperatives, 2020). Similarly, the regional project supported by IFAD and the two agricultural development institutes in Africa has contributed to improving the performance of the rice sector by identifying rice hubs, where the integration of local innovations, research facilities and rice value chains results in positive development outcomes.

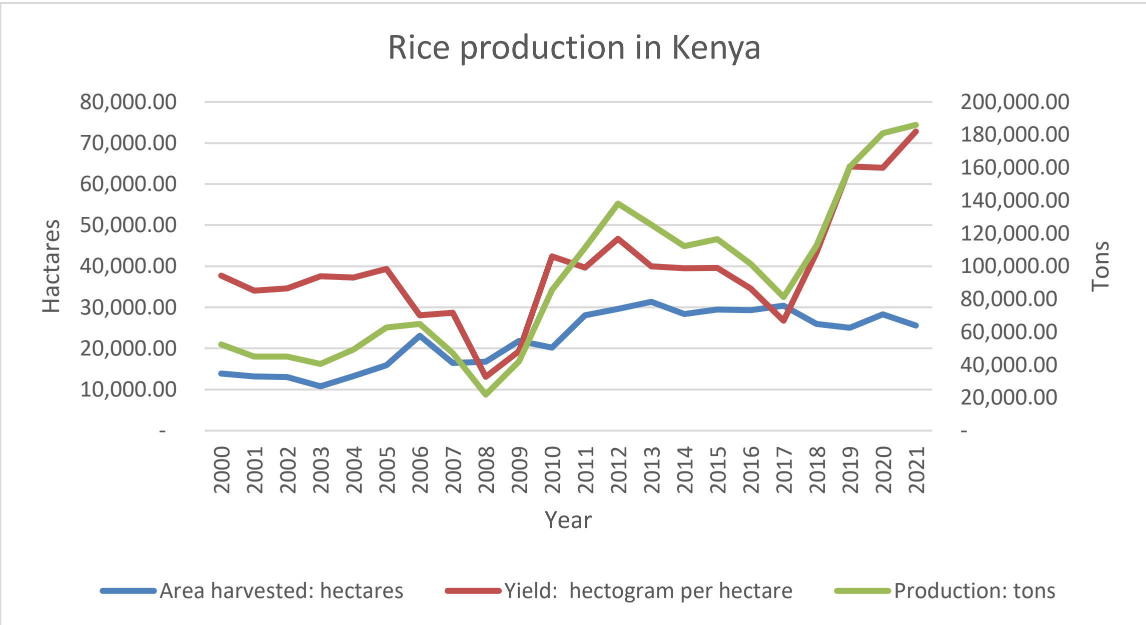

FIGURE 10: RICE PRODUCTION IN KENYA

Source: Adapted from FAO, 2022a

4.2.2.1 Sustainable agricultural practices

The sustainable agricultural practices presented in this section come from the documentary analysis described above and summarized in Appendix 4, which shows where in the agricultural process it is implemented, in what region, to address what problem and how it is impacting economically, socially and environmentally. This section explains the practices and their benefits in depth.

The introduction of sustainable agricultural practices in rice production started in 2004 in Kenya with conservation tillage, which is a farming system with minimal soil disturbance, involving reduced tillage or no tillage at all, which decreases production costs – mainly fertilizer and irrigation systems – due to soil reclamation (Indeche & Ondieki-Mwaura, 2015; NEMA, 2013).

In 2009, two irrigation system practices were implemented: System of Rice Intensification (SRI) and Alternative Wetting and Drying (AWD). SRI was implemented in the country as a multi-institutional collaborative research project (Nyamai et al., 2012) to increase rice productivity by modifying the way nutrients, water, soil and plants are managed, while reducing the use of external inputs (Ndiiri et al., 2013; Ndiiri et al., 2017; Kadipo et al., 2021). It is a locally focused soil-water management practice preceded by research, as it is based on social, climatic, socio-cultural and socio-economic conditions to improve crop productivity (Nyamai et al., 2012, Mbatha et al., 2019). The benefits are reduced costs in land preparation, fertilizer and irrigation, and increased crop yields (Ndiiri et al., 2013). The second practice is AWD, which is used in combination with SRI, as active aeration of the soil is one of the most crucial SRI principles with broad implications for crop growth and output (Nyamai et al., 2012). This practice helps the crop adapt to climate change conditions while reducing its GHG emissions.

In 2013, a practice focused on land suitability analysis was introduced in rice production, which includes the use of Multi-Criteria Evaluation (MCE), Analytical Hierarchy Process (AHP) and GIS approach to find solutions to challenges with many decision-making alternatives, as it includes the evaluation of various production factors that can be individually weighed based on their relative value to generate the optimal circumstances for crop growth (Kihoro et al., 2013). It is a technique that provides an improved database and guide map for decision makers considering crop substitution to improve agricultural production (Kihoro et al., 2013).

Moreover, ten sustainable practices mainly focused on soil recovery were applied in 2015. The first is timing of production for crop protection, which is knowledge acquired by farmers from experience and is used to avoid pests and diseases in the crop (Indeche & Ondieki-Mwaura, 2015). The second is the application of organic manure on crops, as it is a good source of plant nutrients that helps improve soil structure and texture, its application has a long-term positive effect by reducing the need for inorganic fertilizers that negatively affect the soil (Indeche & Ondiekiki-Mwaura, 2015; Indeche & Ondiekiki-Mwaura, 2016). The third is protection of water quality and quantity through improved water management, which reduces crop irrigation costs and improves adaptability to climate change. The fourth is to leave the land fallow, which is a piece of land that is not used for harvesting because it is left for natural soil recovery, which has a positive long-term effect that reduces fertilizer and irrigation costs (Indeche & Ondiekiki-Mwaura, 2015).

The fifth is to retain crop residues, which can be used as organic fertilizer to reduce soil degradation while minimizing production costs. The sixth is crop rotation, which is considered a cultural strategy used by farmers, consisting of a crop rotation of three to four cycles (Tadele, 2017), in which the main advantages are increasing soil fertility and combating important biotic stress factors, such as weeds, diseases and pests (Indeche & Ondiekiki-Mwaura, 2015; Tadele, 2017). The seventh is the Integrated Pest Management (IPM), which consists of a variety of complementary tactics ranging from selective application of chemical pesticides to biological methods that use natural adversaries to control pests (Fahad et al., 2020). The eighth is the recommended rates of fertilizers used by farmers to prevent soil erosion while reducing the use of inorganic fertilizers. The ninth is the practice of using green manure, i.e., after harvesting rice, a fast-growing legume crop (e.g., cowpea or lentils) is planted and then plowed to provide nutrients for the next rice crop (Indeche & Ondiekiki-Mwaura, 2015). The last is the use of rice husk as organic fertilizer, which is a practice that allows farmers to utilize the value of their residues in an environmentally friendly way and, at the same time, access cheaper fertilizers and soil treatments (Cardiff & Meyer, 2018).

Furthermore, two practices were implemented in 2017: intercropping and the Push and Pull system. The first refers to the production in the same growing season on a plot of land of two or more crops, combining mainly rice and legumes (Tadele, 2017), which benefits are improved crop yields, reduced soil erosion, increased water use efficiency and reduced reliance on inorganic fertilizers (Ogutu et la., 2012). The second is a climate-smart agriculture system that uses natural plant compounds that attract insect pests to other host plants that are more resistant than rice, driving them away from the crop (ICIPE, 2015), the result of this practice is efficiency in pest and weed control while maintaining soil fertility (Tadele, 2017).

4.2.2.2 Digital agricultural technologies

The digital agricultural technologies presented in this section come from the documentary analysis described in the methodology and summarized in Appendix 6, which shows in which part of the agricultural process it is applied, in which region, to address which problem, and what solution it presents. The section below explains the technologies in more detail and their advantages.

The introduction of digital technologies in the agricultural sector took place in 2011 in Kenya with the aim of improving productivity in the rice sector and addressing the main problems faced by farmers, such as lack of communication within the value chain, vulnerability to extreme weather events, absence of access to credit financing, limited water resources and lack of knowledge of the soil situation. The first project has been developed by a company called *SunCulture* which focuses on smallholder farmers, providing them low-cost solar-powered irrigation systems that use off-grid solar technology and give reliable access to water, lighting and mobile charging in a single system (Sunculture, 2022).

In 2012, the second project, called the Connected Farmers Alliance (CFA), a public-private partnership focused on increasing the productivity and resilience of smallholder farmers by addressing inefficiencies in value chain management, was launched (Moceviciute & Babcock, 2016). It supports commercial mobile agricultural solutions that improve the relationship between agribusinesses and farmers (Ujuzikilimo, 2021), reducing transaction costs and enabling transactions (payments and loans) through a mobile money system called *M-Pesa*, which emerged as a microcredit program and positioned itself as an important payment infrastructure (Moceviciute & Babcock, 2016; Mann & Iazzolino, 2021).

Moreover, *UjuziKilimo* was founded in 2015 to introduce technologies such as big data, data analytics and data management to modernize smallholder farming practices into precision agriculture (Osiemo et al., 2021). It uses sensors and data analysis tools to enable agricultural data collection and analysis, helping smallholder farmers access quality information to improve productivity and make accurate decisions about their crops (Ujuzikilimo, 2021).

In 2016, two other projects were created, a mobile application and a digital platform. The mobile app is called *CropHQ* and provides smallholder farmers with a space to monitor crop conditions, including loss and profit estimation, a record of farming practices, and ability to communicate with buyers to reduce losses; satellite photos, drone imagery, weather data and a community interaction page are available in the app (Njirani, 2021).

The digital platform is called *Apollo Agriculture*, which employs automated processes technology and machine learning to provide smallholder farmers with access information to increase their profitability; the platform includes advisory services, insurance options, agricultural products and access to finance (Bosilkovski, 2020). The latter, which is one of the main problems for farmers, is done by creating credit profiles of smallholder farmers and collecting satellite coordinates of their fields to verify their identities (Bosilkovski, 2020; Kene-Okafor, 2020).

Furthermore, two projects were launched in 2017, a mobile app and a drone network. The mobile app called *AgroCare* that uses a portable soil sensor to collect big data and apply data analysis to provide accurate soil analysis and customized fertilizer recommendations (Krishnan et al., 2020). This involved setting up a portable sensor lab assigned to farmer centers to provide soil testing services to smallholder farmers, reducing waiting time for reports and using them to better advise on which agro-inputs to choose to increase crop productivity (AgroCares, 2020). The other project is called *ThirdEye*, which creates a network of flying sensor operators equipped with a high-resolution camera, satellite imagery and an algorithm that analyzes the acquired images to locate plants in need of irrigation (Krishnan et al., 2020; De Klerk et al., 2019).

In 2019, the Kenya Agricultural Advisory Platform (KAOP) was launched, which is an integrated web-based platform that produces localized, real-time agro-advice for farmers and other stakeholders using geographic satellite data (KALRO, 2021). The system predicts weather conditions based on historical observations to create agronomic recommendations and distribute them to smallholder farmers via SMS and an online site (KALRO, 2021).

4.3 Conclusion

The rice sector in Colombia has been following programs created by FEDEARROZ – such as AMTEC – to transfer knowledge and provide training to assist farmers in crop planning, the proper use of technology and the implementation of new practices to increase farmers' profitability (Castilla Lozano & Tirado Ospina, 2022). In sustainable agricultural practices, the country has implemented techniques that include organic agriculture, conservation agriculture, agroecology, climate-smart agriculture and transgenic technologies, involving not only the trade union, but also parallel projects with academia and research centers.

As for the use of digital technologies in the rice sector, the country lags behind. Since the creation of AMTEC in 2012, the focus has been on the introduction of basic machinery and tools that can help improve crop productivity. In 2014, digital technologies began to be used in agriculture, but with an investigative approach and only for specific projects, and two years later digital platforms and mobile applications aimed at crop planning and weather conditions predictions began to be launched. Currently the AMTEC 2.0 program is being carried out with a focus on digital technologies, where satellite images, big data and data analytics have been implemented in digital platforms and mobiles applications. Nevertheless, the use of remote sensors and drones has only been implemented in a specific area of the country, which is the most advanced in research.

In a comparison between Kenya and Colombia, Kenya has implemented more sustainable agricultural practices than Colombia, but they have a very similar approach, using conservation agriculture, agroecology, climate-smart agriculture, organic agriculture and transgenic technologies; additionally, Kenya has applied practices of sustainable intensification, integrated agriculture and permaculture. This is in response to the country's geographical situation and its economic dependence on the agricultural sector, as it has limited land area with good fertility levels and also limited water resources, as well as a large percentage of the population living in rural areas and depending on the agricultural sector as a source of income.

Regarding the digitalization of the agricultural sector, since the 2000s Kenya has been using digital technologies as tools to improve farmers' access to information to make better decisions (Mann & Iazzolino, 2021). The ICT sector within agriculture has become a key driver of economic growth, where the government supports partnerships with the private sector and philanthropic organizations to improve financing for smallholder farmers (Mann & Iazzolino, 2021; Baumüller, 2016). Local start-ups, hence, have grown rapidly benefiting from the recent expansion of the local innovation ecosystem in the country, including the establishment of innovation hubs, skilled personnel and access to funding from private investors (Baumüller, 2016).

The most significant learning from Kenya's transition is the importance of partnerships between companies, agribusinesses, NGOs, banks and other stakeholders to create projects with combined services and complementary support programs, where farmers can make better decisions in crop planning and resource use (Tsan et al., 2019; Baumüller, 2016; Osiemo et al., 2021). Similarly, there is a need for policy makers to understand the impact of digital technologies on agriculture to assess potential market disruptions and create policies that enable an inclusive environment and long-term development (Krishnan et al., 2020; Osiemo et al., 2021).

In terms of the challenges of the innovation ecosystem in Kenya, there are four key issues. Some start-ups have not been able to scale their businesses due to lack of funds to hire people with the right expertise and knowledge (Baumüller, 2016). There continues to be a lack of mentoring and training opportunities with cross-disciplinary courses to help bridge knowledge gaps (Baumüller, 2016; Osiemo et al., 2021). There is a lack of better understanding of customer needs and market context. There is still a need to improve mobile network and Internet access, especially in rural areas, which continue to lag behind in the implementation of digital solutions (Baumüller, 2016).

Therefore, this study analyzes the case of Kenya and presents recommendations to Colombia, with the objective of understanding the lessons learned from the country and the challenges to expand the use of digital technologies in the agricultural sector, especially for smallholder farmers. The recommendations from Kenya to Colombia are found in Appendix 7, where not only digital technologies are recommended, but also sustainable practices that can complement the country's current practices. However, emphasis is placed on projects that include several digital technologies, as it is in this field that Kenya demonstrates the most experience and expertise. The country's success in implementing digital technologies includes the involvement of different stakeholders, proper training of communities and digital literacy of the youth, in addition to the innovation ecosystem that has been created in the country.

5 INTERVIEW ANALYSIS

This chapter presents the analysis of the interviews with Colombian experts. There is a brief description of the organizations represented in the interviews, with the programs and projects carried out by them to understand the role of the actors in the rice sector, followed by the problems encountered and some suggestions to improve production according to the experience of the interviewees.

5.1 Description of interviewees

The stakeholders analyzed in this study are two NPOs, the trade association represented by two organizations and the public sector with one national entity and one government institution.

ASOCARS (I1) is an NPO that represents the regional autonomous corporations, whose main objective is to articulate the positions of the country's environmental authorities and to represent them at the national level, these corporations manage the environment in the regions in accordance with the national development plan. ASOCARS' objective is to address environmental practices from a technical point of view – bringing professionals and technicians to rural areas – to preserve the environment and improve the productivity of the regions.

DAC (I2) is an NPO focused on food sovereignty, environmental protection and the economic and social well-being of rural inhabitants, establishing communication between farmers and the government, as well as between public and private entities to negotiate along supply chains in favor of farmers. The organization is focused on research, currently conducting a project to improve the process of drying rice on the farm, and is also part of a working group with other public entities to provide a roadmap to identify challenges in sustainable agricultural practices and digital technologies immersed in it, with the aim of making decisions to reconcile the productive and environmental sector at the national level.

The trade association FEDEARROZ (I3) represents rice growers at the national level. Its objective is to encourage farmers to carry out good agricultural practices, promoting technological development, seeking economic efficiency and greater competitiveness. The FNA (I7) is a special account for the collection and management of the resources of the Rice Development Quota, whose activities for farmers are directed by a committee made up of representatives from different national ministries. FEDEARROZ-FNA is currently working on the implementation of rice certifications, focusing on food safety, traceability and food security issues. It also conducts crop research in areas such as soil, water and climate management, with FNA resources from farmers. In addition, the union conducts studies on traceability of heavy metals and traces of agrochemicals in grain to determine which pesticides remain in the grain until it is marketed and consumed to limit their use. Lastly, FEDEARROZ-FNA has a program called AMTEC, whose main objective is to reduce production costs and increase yields by measuring GHG emissions to apply best practices in all crop areas to reduce emissions, mainly through a farmer-to-farmer technology transfer model.

Representing the public sector, the MADR (I4) is carrying out different projects related to the agricultural sector. The ministry is working on a regulatory project to reduce food loss and waste through the design of a comprehensive public policy whose implementation mechanisms are to be established. The MADR has also made public purchases and projects that encourage producers to sell their harvest directly to the ministry, as well as negotiations to connect producers with large processors or market chains. There is also a project with a government entity called the Colombian Institute of Family Welfare (ICBF) that wants to take advantage of the harvest that is not sold or the products that are damaged in transport – but are still in good condition – to take these food products to kindergartens.

On the other hand, the ministry is working with a public entity called the Colombian Corporation for Agricultural Research (AGROSAVIA), to make more efficient use of agrochemicals due to the increase in prices, however, more work is needed and it is considered an opportunity for organizations to conduct research to generate new practices and technological packages. Finally, the ministry is working with the information and communication network of the Colombian agricultural sector to get to know new users and their needs, in order to improve the content of information that is provided to the sector.

Finally, the national entity called UPRA (I5, I6) supports the MADR by generating instruments and criteria for agricultural land use planning and managing information systems that define the agricultural frontier. UPRA also works with the trade unions to identify areas of aptitude for different production systems, using criteria related to environmental sustainability. Moreover, the entity has developed a Rural Agricultural Planning Information System (SIPRA), which is a geographic viewer to obtain information on where to grow crops and what products to grow, considering aspects such as soils, climate, irrigation and infrastructure, and prepared guidelines for family agriculture focused on agroecology concepts. In the future, UPRA wants to carry out a crop monitoring project, for which it is necessary to strengthen technologies, develop algorithms and have greater precision in the way images of crop behavior, production and yields are interpreted. It is therefore essential to consolidate technological knowledge, increase the availability of technologies and generate greater exchange with countries that already have more developed technologies.

5.1.1 Problems in the rice sector

The problems mentioned by stakeholders are the lack of soil analysis to regulate the use of pesticides and fertilizers (I2, I5, I6, I7), inadequate water management (I2, I6, I7), the absence of digital platforms designed for smallholder farmers (I2, I4, I5, I6, I7), and the drying process in rice production (I2, I3).

Soil analysis is important for rice production as it can reduce production costs by reducing pesticides and fertilizers applied to the soil (I1), but it requires high investment in equipment, so its use is rather poor and limited (I1, I6). Likewise, farmers do not use soil analysis as a tool to properly guide their fertilization, but rely more on technical assistance provided by the commercial company that sells fertilizers (I6).

Water management is one of the most fundamental aspects of rice production, but irrigation in Colombia is deficient. The country has barely one million hectares irrigated and generally uses diesel pumping or gravity irrigation (I6). Irrigation requires investment in diverse machinery that smallholder farmers cannot afford due to the variability of market prices, which in most years are low and inefficient for such investments (I2). Added to this, water scarcity – due to climate variability – is one of the main concerns of farmers, as it can cause crop stress (I7).

Furthermore, more research is needed to take advantage of digital technologies and ensure their extensive use by identifying and segmenting needs (I4, I5). Rural areas in Colombia have many connectivity problems, so many of the equipment, tools and platforms that can provide support or information to farmers do not work in rural areas (I7). Because of this, digital platforms need government support to help all agricultural producers, without focusing only on large cities (I2).

Finally, there is a bottleneck in rice production in the post-harvest process, as the rice must be dried immediately, but farmers do not have adequate storage to carry out the drying process on the farm (I2). If the product is not dried in less than twenty-four hours, production is lost, so farmers must accept whatever the drying industry wants to pay them in order not to lose production (I3).

5.1.2 Suggestions for improvement

The first suggestion made by interviewees for the rice sector is to focus on reducing production costs, including seeds, machinery and agricultural inputs. This can be done through more efficient use of pesticides and fertilizers (I2, I4), creating more pest control strategies (I7), efficient water management (I7), strengthening the technical assistance system (I4), and creating technological packages that improve the country's productivity (I4). Likewise, bringing affordable soil analysis equipment to rural areas (I2), while generating a strategy to make soil analysis one of the most widely applied practices by all farmers to reduce the excessive use of agrochemicals (I6).

Another suggestion is to promote research to understand what digital technologies are needed in the agricultural sector (I5), and to make a classification of practices, from those that can be done by any farmer to those that require prior knowledge (I3). Similarly, a suggestion is to create digital platforms with the support of stakeholders focused on rural areas (I2) and generate strategies to increase the use of digital technologies to make them accessible to all farmers, especially smallholder farmers (I5). This would incentivize young people to develop a farming business with better information and digital technologies available (I6). The last suggestion is to promote partnerships among smallholder groups so that they can make investments in machinery and digital technologies (I3), while overcoming connectivity problems at the national level so that digital technology tools can be used in rural areas.

6 DISCUSSION OF THE FINDINGS

This section aims to analyze the information presented in the case study with in-depth expert interviews. First, the state of the art and the main causes of food loss in the rice sector in Colombia are presented, succeeded by the implementation of sustainable agriculture practices and digital agriculture technologies, considering challenges and obstacles. This is followed by an evaluation of the recommendations provided by the Kenyan case to the Colombian case, emphasizing how each of them addresses the main environmental, social and economic issues that are key to improving production in the rice sector. Additionally, an evaluation is made according to the level of environmental emergency addressed by the recommendation, and the level of knowledge and investment required by farmers to implement them to understand the feasibility of the recommendations in the Colombian case. Finally, additional solutions and lessons learned from the Kenyan case are provided to improve production in the rice sector in Colombia.

6.1 Food loss

According to the documentary analsys, 34 percent of food is lost in Colombia, where the main causes for the rice sector are poor demand forecasting that generates overproduction, premature harvesting due to economic needs, delayed harvesting caused by pests and diseases, incorrect soil management that affects yields, and variable climatic conditions. This generates consequences such as being one of the crops that has caused loss of tree cover in the Orinoquia region because of the transformation of land to agricultural practices, as well as excessive water consumption due to irrigation, which is the main cause of water withdrawals for agriculture.

In congruence, all interviewees agreed that there is food loss in Colombia, and that the main causes in the rice sector are price instability (I2, I3, I4, I5, I7), deficiencies along the supply chain (I2, I6, 17), lack of proper infrastructure and adequate agronomic practices (I3, I5, I6, I7), and unstable climatic conditions (I1, I2). According to (I1), food loss is considered a problem because it increases deforestation, as the agricultural frontier must be expanded to produce more food, as well as increases malnutrition, as production is not efficient and food does not reach the final consumer.

In two interviews, it was mentioned that market conditions keep rice prices low because there is no synchronization of crop planning and harvest cycles with the domestic market (I2, I6). Likewise, farmers do not have access to credit to invest in better practices, i.e., it is not possible to invest without high risk (I2), agro-inputs are more expensive due to external shocks (I2), and there is a low level of farmer education, with an older generation in the field and young people leaving rural areas (I3).

In addition, there is an absence of support for domestic agriculture by the government evidenced by the lack of prioritization of national infrastructure and connectivity in the country to develop better communication between rural and urban areas, maintaining problems such as power outages and damaged roads that generate delays and food loss (I2, I7). Lastly, there is a lack of consideration of ecosystem security and food safety (I1) and no awareness of the causes and consequences of food loss in the sector (I4).

6.2 Sustainable agricultural practices

The documentary analysis shows that the introduction of sustainable agricultural practices in Colombia began in 2002 and focused mainly on crop nutrition with the introduction of biofertilizers, and later on crop rotation, the use of agricultural residues for fertilization and the application of the recommended rate of fertilizers. Two water management projects were also generated, one for organic rice production that reduced water consumption, but was discontinued after five years of application, and another called AWD that alternates flooded and non-flooded conditions, which is still in use. In addition, there has been a project in which scientists have collaborated with FEDEARROZ to provide farmers with an analysis of weather and crop conditions, which resulted in avoiding crop failure due to a drought but was a one-time project.

All interviewees agreed that there is some progress towards sustainable practices in the rice sector in Colombia, but much remains to be done in terms of coordinated efforts between the productive and environmental sectors (I1), including new practices and technological packages to improve the country's productivity (I4). There is an influence of international markets and international commitments, which seek to standardize processes to comply with sustainable production, which encourages rice producers to be more conscious of the environment where they produce (I3, I6). Similarly, trade unions play a key role in managing and learning to implement smart agriculture (I5), producing in a more environmentally friendly way (I6) and focusing on monitoring to determine pathogens and pests (I7). However, there is still a need to improve smallholder farmers' access to environmental education that gives them the opportunity to ensure food security while restoring nature (I1).

According to interviewees, the challenges in implementing sustainable agricultural practices involve regulations (I1, I2, I5, I6), lack of technical assistance (I2, I4, 15), farmer education (I1, I3, I5, I6), access to technologies (I1, I4, I5, I6), rejection of the culture (I1, I3, I4,) unfavorable climatic conditions (I2, I3) and negative economic situation (I3, I4, I7). One of the lines of action to facilitate the implementation of sustainable practices is to implement regulations that reinforce and promote an environmental culture (I1, I6), as well as government support with resources and budget to help small producers, particularly to deal with environmental risks such as natural disasters and the consequences of mining or fracking (I2, I3). Also, technical assistance and education (e.g., access to information and programs) is needed particularly for smallholder farmers (owners of five hectares or less) to encourage sustainable production and access to technology (I1, I4, I5, I6). With the above actions, it would be easier to initiate a cultural acceptability and increase an economic motivation to implement sustainable practices (I1, I3, I4, I7).

6.3 Digital agricultural technologies

The documentary analysis demonstrates that the implementation of technologies for agriculture began in 2012 in Colombia focusing on machinery to improve rice production. However, in 2014, the introduction of the first mobile application to collect information on agricultural practices and provide advice began. That same year, a digital platform was created to give personalized recommendations on the amount of fertilizer to apply to the crop based on geographic location. In 2015, remote monitoring of irrigation systems was also initiated with data recording, processing, tabulating it in a computer system and sending it to farmers via the Internet. As well as the introduction of high-resolution soil maps and satellite images of the lots one year later, subsequently including projects that unify technologies using mapping tools and drones to create a spatial representation of yield data in real time. There are currently three digital platforms in the rice sector, one focused on fertilization, another on weather forecasting and the last one on documentation management and communication with entities within the sector.

Although all interviewees agreed that digital technologies play a key role in increasing productivity in the agricultural sector while implementing sustainable practices. There are some gaps in farmers' capacity to use them (I5, I6). Additional strategies should be sought for smallholder farmers to adopt the technologies, combined with training and knowledge transfer, as well as the generation of appropriate technology packages for each crop (I3, I4). Similarly, the country's digital infrastructure is not ready for a technological transformation as noted by all interviewees, highlighting the lack of connectivity in rural areas (I3, I4, I5, I7), the absence of machinery and tools for proper food handling in the sector (I2, I6), and insufficient applications and development due to a shortage of adequate training and knowledge transfer (I4, I5, I6).

The obstacles faced in Colombia for the implementation of digital technologies in the agricultural sector include farmers' access to technology (I1, I2, I3, I4, I5, I7), the economic condition of farmers (I1, I3, I4, I5, I7), government support (I1, I2, I3, I4, I5, I6, I7), limited connectivity (I3, I4, I5, I6, I7) and the generation gap in rural areas (I2, I6).

Regarding farmers' access to technology, it is essential to understand farmers' constraints, in terms of resources, finances and agronomic practices, to access digital technologies (I2, I4, I7), as well as their cultural barriers to recognize how to introduce new technologies to them, as not all farmers have the same technological level to adopt them (I3).

As for the economic condition of farmers, there is a need to provide them with financial credits and subsidies (I2), since economic instability makes them focus on production and profit instead of social and environmental aspects (I1, I3). Also, the smallholder segment needs to be better understood, as they do not have the resources and liquidity to make the necessary investments for digital technologies (I3, I4, I7).

In terms of government support, it is necessary to strengthen intra-institutional and inter-institutional articulation and synergy, as well as to improve international cooperation in the governance of natural resources (I1), which implies reevaluating the impact of FTAs on Colombian producers (I2). In addition, identifying the needs and the segment of farmers to develop the appropriate technology and ensuring the transfer of knowledge to rural areas with a clear and practical language are important (I3, I6). Although there is still a long way to go from research and practice to achieving changes in the agricultural sector (I5), a key aspect is the scaling up of emerging technologies from the private sector to smallholder farmers with research and transfer programs, where different institutions have the technical and financial facilities to acquire the technology and disseminate it to farmers (I1, I7).

Furthermore, network coverage with internet access is one of the main barriers for the sector in introducing digital technologies (I3, I4, I5, I6, I7). Without improving the country's connectivity, both in terms of roads and Internet networks, it will be difficult for the agricultural sector to migrate to digital agriculture (I7). Lastly, the rural generation is aging and young people are leaving the countryside in search of better economic conditions (I2, I6), which is a problem because young people are easily familiarized with digital technologies and the countryside is becoming sparsely populated (I6).

6.4 Assessment of the recommendations

The assessment of the recommendations is carried out by selecting the main problems facing the rice sector according to the case study and expert interviews, differentiated by economic, social and environmental aspects. Table 5 shows how the problems are divided. In the economic category, the main problems faced by farmers are reduced crop yields, low market prices for rice, difficulty in finding quality seeds, lack of financial support for smallholder farmers, high-risk investments to introduce digital technologies, and high production costs due to high prices of agro-inputs, machinery and seeds.

The social category refers to the knowledge and training a farmer must have to apply new practices, including knowledge of how to fertilize crops, how to prevent and avoid pests and diseases, understanding soil variability and seed placement, understanding the importance of monitoring soil nutritional status, knowing and applying good agricultural practices, having the expertise to make difficult decisions in unclear situations due to the difficulty of reaching all the areas of the crop, and understanding weather forecasts. The environmental category focuses on water and land management, firstly to prevent water shortages, create water availability in difficult areas and provide irrigation to more areas of the country, and secondly to know soil nutrition and prevent soil erosion. See Appendix 10 for the evaluation of each recommendation based on these factors.

Category	*Problems*
Economic	Crop yields
	Prices
	Seed quality
	Financial support
	Investments
	Production costs
	Collect information to analize crops
Social	Fertilize crops
	Pest and disease control
	Soil variability
	Seed placement
	Monitor nutritional status
	Agricultural practices
	Make difficult decisions under unclear situation
	Weather forescasting
Environment	Water scarcity
	Water in difficult access areas
	Irrigation
	Soil nutrition
	Soil erosion

TABLE 5: CATEGORIZATION OF PROBLEMS IN THE RICE SECTOR

Source: own work

After evaluating each recommendation according to its contribution to the solution of the rice sector's problems, an additional evaluation is made on the importance of the recommendation to address an environmental emergency, as well as the level of knowledge and investment required by farmers to implement them, in order to understand the viability of the recommendations in the Colombian case. Table 6 shows the analysis, which is done using a color code developed by the researcher based on the information obtained from the literature review, case study and expert interviews. Red means that the recommendation has a high impact with respect to an environmental emergency for the rice sector, and also means that the level of farmers' knowledge to implement this recommendation is high, as well as the level of economic investment. While yellow evaluates these three aspects with a medium level and green with a low level for the required knowledge and investment, but also a low impact in addressing an environmental emergency.

Recommendations			
Solution	Level of environemntal emergency	Level of knowledge	Level of investment
System of Rice Intensification (SRI)			
Push and Pull system for pest control			
Intercropping			
Conservation tillage			
Rice husks as fertilizer			
Solar-Powered Irrigation System			
Soil analysis system			
Digital platform: improving the efficiency of both agribusinesses and the smallholder farmers			
Digital platform: using satellite data and machine learning to improve smallholder farmers productivity			
Mobile application: functioning as an advisory tool for farmers			

Level of knowledge	*Level of investment*
Low	Low
Medium	Medium
High	High

TABLE 6: ANALYSIS OF RECOMMENDATIONS

Source: own work

There are ten recommendations in total, where the first five of table 6 belong to the sustainable agricultural sector, while the last five to the digital agricultural technologies. The five sustainable agricultural practices focus on water management, pest control, soil conservation and organic fertilizer; which are the SRI for water management; push and pull system for pest control; intercropping for soil recovery; conservation tillage for preventing soil damage; and rice husk as fertilizer for low-cost organic fertilizer. The level of environmental emergency addressed is medium in almost all sustainable practices, except for SRI, which is high. The level of knowledge varies from low in the case of intercropping and conservation tillage to medium in the remaining three. The level of investment is low in almost all of them, except for rice husk as fertilizer, which is high.

As for the digital agricultural technologies, there are five recommendations that are focused on irrigation system, soil analysis, business development and advisory tools for farmers, these are the solar-powered irrigation system; the soil analysis system; a digital platform to improve the efficiency of both agribusinesses and smallholder farmers; another digital platform that uses satellite data and machine learning to improve the productivity of smallholder farmers; and a mobile application that functions as an advisory tool for farmers. The level of environmental emergency addressed is high for the solar-powered irrigation system, medium for the soil analysis system, and low for the digital platforms and the mobile app. The level of knowledge required to implement these recommendations on a day-to-day basis on farms is high in almost all of them, except for the solar-powered irrigation system, which is medium, while the level of investment is high in the first two and medium in the digital platforms and mobile apps.

The first recommendation is the implementation of the SRI in the country. There was already an attempt in Colombia in 2016 as a research project, but it was stopped and is currently not implemented. The project demonstrated the benefits of the practice; however, the methodology must be adjusted for application in production under local conditions. Therefore, it is necessary to know the region very well, make a soil analysis, a soil nutrition plan and a focus on weed control. Although it is not scalable to large extensions because it requires a lot of labor force, the cultivation system is suitable for smallholder farmers (with less than 3 or 4 hectares), as it is a manual farming practice.

In terms of economic benefits, it helps increase crop yields. However, the skills needed to implement the recommendation are crop fertilization, pest and disease control, nutritional status monitoring and good agricultural practices. Environmental management focuses on water scarcity, promoting access to water in difficult areas, increasing soil nutrition and prevention of soil erosion. This is an agroecological practice that addresses the environmental emergency with high impact in the rice sector, requiring a low level of investment and a medium level of knowledge. Thus, given the importance of water management in the rice sector and the number of small farmers in the country, it is a practice that can be implemented with technical assistance.

The second recommendation is the push and pull system for pest control. In Colombia, pest control is mainly done by chemical control due to the size of the field, and also by mechanical control.

Although FEDEARROZ emphasizes pest monitoring and the use of thresholds to avoid inappropriate use of chemicals in the field, the sustainable practice mentioned was unknown to the interviewees. It is a climate-smart agriculture system developed by the International Center for Insect Physiology and Ecology (ICIPE) in Kenya, which uses natural plant compounds to attract rice insect pests to other, more resistant host plants.

In terms of economic benefits, it helps increase crop yields, but knowledge such as crop fertilization, pest and disease control, seed placement, nutritional status monitoring and good agricultural practices are needed. As for the positive impact to the environment, it is realized by preventing soil erosion. Therefore, the impact of the environmental emergency is medium, requires a medium level of knowledge and a low level of investment. This practice, which can be applied with technical assistance in Colombia, has been successful in Kenya and can help farmers reduce pesticide application, improve crop productivity by controlling insect pests and maintain soil fertility by releasing essential plant nutrients from these more pest-resistant plants.

The third practice is intercropping, an alternative that combines cereals with legumes to reduce soil erosion, increase the harvest quantity of both crops, diversify the diet increasing food security, increase soil fertility as legumes provide nitrogen to the soil and reduce dependence on chemical fertilizers. In Colombia, intercropping is not implemented, but crop rotation in rainfed areas through a program promoted by the MADR for pest management, improved profitability and reduction of excessive production cycles. It is a practice that depends on the available water; if there is not enough water supply, in most cases the lot is left to feed cattle, and in some cases, it is rotated with crops that have lower water needs than rice, such as corn, beans, soybeans, sorghum, or the lot goes fallow.

In terms of economic benefits, it helps increase crop yields, where the skills needed to implement the recommendation are nutritional status monitoring and good agricultural practices. The environmental management performed consists of increasing soil nutrition and prevention of soil erosion. This practice requires a low level of knowledge and a low level of investment, while it has a medium impact in addressing environmental emergencies in the sector. Therefore, intercropping is a practice that can be applied in places where crop rotation has already been carried out, but where legumes are grown at the same time as rice; it is a practice that can be explained in farmer training, emphasizing the benefits that can be achieved.

The fourth practice is conservation tillage, which is a method that reduces soil disturbance to minimum levels. In Colombia, FEDEARROZ focuses on reducing the amount of tillage, and in case it is done, that the tillage has multiple purposes, e.g., a good tillage or a good adaptation allows maximizing water efficiency and increasing irrigation speed, so that in less time a larger area is irrigated with a smaller amount of water; which is one of the main motivations for soil preparation and adaptation. Hence, conservation tillage is a practice that is considered in the rice sector, but more awareness needs to be raised among farmers through training; not only explaining how to do it, but also showing concrete results.

In terms of economic benefits, it helps to increase crop yields, while the knowledge required to implement the recommendation is crop fertilization, nutritional status monitoring and good agricultural practices. As for the positive impact on the environment, it occurs by preventing soil erosion. This practice requires a low level of knowledge and a low level of investment, while it has a medium impact when dealing with environmental emergencies in the sector.

The fifth practice is the use of rice husks as a low-cost organic fertilizer. This is a process that consists of collecting crop residues, transforming them into biochar, adding a local enzyme and converting them into fertilizer to be applied to the rice crop while reducing production waste. The project was achieved in Kenya due to the involvement of different stakeholders, a company that has a business idea, a government organization that helps with initial testing and training of farmers, and a university that provides research, funding and skills training (Cardiff & Meyer, 2018).

In the case of Colombia, rice husks are not yet used as fertilizer because of the risk of generating cross-contamination as the husk must undergo thermal treatment or composting to kill or control all pathogens and turn it into fertilizer. Likewise, in the country the milling industry uses 60 percent of the husk as an energy source for grain drying towers and 30 percent is used for stables and cattle corrals, but it is not used to nourish or fertilize the crop again (I7). However, one of FEDEARROZ's plans for the future is to use rice husks as a source of nutrients to make fertilizers, so the Kenyan case can be an example to build on and adopt to local conditions.

In terms of economic benefits, it helps increase crop yields, reduces production costs and increases the capacity to make investments. The knowledge required to implement the recommendation are crop fertilization, pest and disease control and good agricultural practices. As for the positive impact on the environment, it consists of increasing soil nutrition. This practice requires a medium level of knowledge, but a high level of investment due to the thermal process to allow microbial growth and generate fertilizer, while it has a medium impact when dealing with environmental emergencies in the sector.

The first digital technology recommended is the use of solar-powered irrigation systems, which is a technique to help irrigate crops using off-grid solar technology; the components are a motor pump, a solar panel, a reservoir and an irrigation system. In Colombia, solar pumping has been tested, but there are two main problems for its implementation, the rice crop demands a lot of water in volumetric terms, so a large motor pump would be needed, which would imply a large number of solar panels; and the electronics of the motors, since the highest consumption is given to start the motor, which makes the use of panels technically and economically unfeasible. Experiments have been made with mixed modalities in which the energy supplied by the grid is used to start the motors and when the motor is running the solar panel comes into operation, but this is only feasible where there is electrical infrastructure nearby; another option is to use batteries, but this makes the system considerably more expensive. Hence, small demonstrations have been made in the country, but it is not a practice that is used on a daily basis in any agricultural area and without alternatives to those mentioned above, it is a technique that is unlikely to work in Colombia.

The second is a soil analysis system that provides fertilizer recommendations based on soil data collected through a handheld scanner; its components are a mobile application, a portable soil sensor, big data analysis and machine learning to provide accurate soil analysis. In Colombia, soil analysis is one of the most recommended practices, but it is one that is rarely implemented in the field, in the country there are laboratories distributed in different regions, but for rural areas it is still difficult to reach them. Currently, due to the increase in fertilizer prices, there is a possibility that farmers may increase soil testing as a practice to use fertilizers sparingly following a technical evaluation. Therefore, this is a project that can be executed in partnership with FEDEARROZ for technical assistance and FNA for investment in equipment focusing on smallholder farmers in remote areas.

In terms of economic benefits, it helps increase crop yields, while the knowledge needed to implement the recommendation are crop fertilization, pest and disease control, soil variability, nutritional status monitoring, good agricultural practices and understanding how to make difficult decisions in unclear situations. As for the positive impact on the environment, it consists of increasing soil nutrition and preventing soil erosion. This practice requires a high level of knowledge and a high level of investment, while it has a medium impact when dealing with environmental emergencies in the sector.

The last three recommendations, two digital platforms and a mobile application, are used as advisory tools for farmers with different combinations of elements including, mobile payments, community page, business data collection and analysis, insurance, agricultural products, financing, agricultural reports, crop analysis, weather reports and profit and loss projections. For the Colombian case, attempts have been made to develop platforms, but they need to be improved, similarly, rural areas in Colombia have many connectivity problems, so farmers have to travel to urban centers to have Internet connection and be able to consult weather forecasts, check prices, consult disease and pest monitoring results, among others.

In terms of economic benefits, it helps regulating prices, providing seed quality, giving financial support to farmers and reduction production costs due to the reduction of intermediaries. For the mobile application, knowledge is required in pest and disease control, nutritional status monitoring and weather forecasting, for all three making diificult decisions in unclear situations. All three do not have any direct positive impact on the environment. These practices require a high level of knowledge relating to digital literacy and a medium level of investment, but they have a low impact when dealing with environmental emergencies in the sector. Therefore, technology can help disseminate better practices in the agricultural sector, improving access to information and aggregating different types of data. But additional strategies need be found to introduce digital technologies among smallholder farmers and in hard-to-reach areas due to issues such as the connectivity problem faced by many rural areas of the country.

After evaluation of the recommendations, the analysis shows that sustainable agricultural practices are not addressing some of the economic issues facing the rice sector, only crop yields, leaving behind low market prices, poor seed quality, lack of financial support and high production costs. While digital platforms and mobile application focus on economic benefits, but are not having a direct impact on water and/or land management. What is needed for all of these is knowledge or adequate training in crop fertilization, pest and disease control, nutritional status monitoring and good environmental practices to be able to implement the recommendations.

For addressing the problems encountered in the rice sector in Colombia, the Kenyan case provides additional solutions and lessons learned. First, the importance of government support for creating policies that enable an inclusive environment and long-term development. Second, providing training to improve agricultural practices focusing on smallholder farmers. Third, the promotion of partnerships between smallholder farmers to invest in the practices that better suit its needs. Fourth, the introduction of digital technologies that emphasis of improvement in land management (e.g., soil analysis) and water management (e.g., irrigation). Last, the improvement of communication between stakeholders and creation of partnerships to create projects with combined services and complementary support programs for farmers.

In addition, Kenya is aware that it can still further improve its rice production, so it has some solutions to implement in the future following the Agricultural Sector Transformation and Growth Strategy (ASTGS) from 2019 to 2029. Among its key points is the recognition of problems such as post-harvest food losses, water management, farmer training and economic conditions. Post-harvest losses are reduced with the creation of small and medium-sized storage facilities, along with best practices in handling and storage of produce. Water management is also addressed with the construction of new dams with alternative water supply approaches to increase water storage, while helping small farmers gain access to irrigation equipment. To improve the economic conditions of farmers, an electronic voucher system is established with a registration process for the purchase of agricultural inputs. To increase farmer training in good practices, technical and non-technical training is provided with a cross-sectoral approach.

7 CONCLUSION

The agricultural sector is essential for the development and preservation of humanity, but its production is neither sustainable nor efficient due to the improper use of agrochemicals, inadequate agronomic practices, inefficient infrastructures, limited information, overproduction and variable climatic conditions, which currently deteriorate the environment by reducing soil fertility, water availability, biodiversity and natural resources, while increasing GHG. At the same time, population growth is a trigger for increased food production to meet global demand and ensure food security, making production unsustainable and leading to food loss along the agricultural process, generating more waste and pollution and contributing to climate change, land use change, freshwater depletion and biodiversity loss.

Food loss generates negative economic, social and environmental consequences caused by limited physical infrastructure, lack of training, inadequate agronomic practices and unforeseen weather conditions. Although research in the field of food loss is insufficient, its reduction is required to improve the productivity of the agricultural sector and reduce the need to expand agricultural production on protected lands such as forests or nature reserves. Hence, sustainable agricultural practices and digital agricultural technologies are tools that can help reduce the causes of food loss in the agricultural process, improving crop productivity, increasing food security and nutrition, and reducing the use of natural resources and GHG emissions.

This study evaluates the rice sector in Colombia, identifying the main problems on-farm processes that lead to food loss and hinder sustainable production. The country has the potential to expand its food production without affecting its natural resources, biodiversity and land availability, but current agricultural productivity is low, affecting the economy and quality of life of farmers, national food security and nutrition, and natural resources by triggering deforestation. The rice sector has potential to improve yields, but there are environmental, social and economic problems that limit its production.

On the economic side, low crop yields, low market prices for rice, lack of financial support for smallholder farmers, high investments to introduce digital technologies, and high production costs due to high prices for agricultural inputs, machinery and seed. On the social side, lack of knowledge on how to fertilize crops, prevent and avoid pests and diseases, monitor soil nutritional status, and understand weather forecasts. On the environment side, lack of soil analysis to regulate the use of pesticides and fertilizers and prevent soil erosion, insufficient water management during rice production and lack of storage facilities for the drying process.

Some recommendations were provided by the Kenyan case to the Colombian case in order to implement sustainable agricultural practices and digital agricultural technologies to achieve a sustainable agriculture in the country. The analysis shows that the sustainable agricultural practices provided are not addressing some of the economic issues facing the rice sector, while digital agricultural technologies focus more on economic benefits, but are not having a direct impact on water and/or land management. What is needed for all the recommendations presented is knowledge or adequate training.

The advantages of digital agricultural technologies are facilitating access to knowledge and information to improve decision making, enhancing communication with stakeholders, improving access to credit, payment methods and insurance, and monitoring crops to identify risks at an early stage. However, some limitations to its implementation are connectivity problems in rural areas, lack of training of farmers to understand all services, large investments in equipment, battery limitations in large areas, difficulty of operations in bad weather and difficulties in data collection in rural areas due to lack of standardization. As well as the risk of increasing inequality among farmers due to the different economic capacity of the sector.

Mobile devices are used to improve communication with stakeholders and improve traceability of production, making it easier to measure food loss, and they can also improve access to credit, payment methods and insurance. However, connectivity problems in rural areas limit their use, as does the lack of training to take advantage of all the services. Remote sensing technologies are used to monitor crops and identify risks at an early stage, especially pests, diseases and droughts, but they cannot operate over large areas due to battery and range limitations, as well as the difficulties of flying in bad weather. Big data is used to analyze large amounts of data and improve decision making by searching for patterns and creating models, nonetheless, the lack of standardization to analyze the data after collecting it is a limitation, as well as large investments are needed to process and store the data, and staff with specific knowledge and training.

Additionally, according to the recommendations, there is no use of integration and coordination systems, nor intelligent systems such as robots, autonomous systems, Deep Learning and AI. Although it could be due to the lack of knowledge and training of these technologies in agriculture, the economic capacity of the farmers makes them unable to invest in these technologies due to the complexity of their implementation and the high investment cost.

The goal is to generate digital agricultural technology packages adaptable to the sector and create digital platforms focused on smallholder farmers with technologies that can be used offline. Digital technologies are only a tool and alone will not make agricultural production more sustainable. The implementation of digital technologies should be handled with caution to avoid increasing inequality in the rice sector between large farmers – who have the capacity to invest in the latest digital technologies, and smallholder farmers, who are located in the most remote areas, without access to credit and with problems of road infrastructure and connectivity; being them the most prone to have problems in production and food loss. Consequently, it is important to promote partnerships among smallholder farmers to achieve investments in equipment and training to improve production, as well as to provide digital technologies appropriate to their needs.

By improving on-farm practices, food loss will be reduce and farmers will improve their productivity and also their income, giving them the possibility to invest in digital agricultural technologies to manage the most complicated issues: water availability and soil analysis. However, it is not only necessary to invest in digital technology to make agriculture more sustainable, there are also other practices that help farmers improve production with the support of stakeholders such as providing training, contributing to research, offering funding and monitoring farming practices.

For the successful implementation of practices, public-private partnerships that combine the strengths of both parties are needed to provide research and funding opportunities focusing on the main problems of the rice sector and introduce technologies to improve land management (e.g., soil analysis) and water management (e.g., irrigation). At the same time, government support to improve road infrastructure, connectivity and electricity in rural areas, as well as the creation of policy frameworks focused on long-term structural reforms, such as strengthening the agricultural innovation system and greater integration within agri-food markets. Similarly, providing training to improve agricultural practices focusing on smallholder farmers, as well as assisting in the construction of post-harvest infrastructure on farms. Lastly, the improvement of communication between stakeholders and creation of partnerships to create projects with combined services and complementary support programs for farmers. Focusing on reducing food loss to improve practices in the agricultural sector equips the various stakeholders (e.g., unions, farmers, policy makers, service providers) with tools to prioritize the needs of the sector through training, knowledge transfer and appropriate subsidies.

7.1 Limitations of the research

The limitations of the study were encountered during the decision-making process to define the methodology of the thesis. The first is the geographical scope, in which two developing countries were selected, one in Latin America and the other in Sub-Saharan Africa. The selection was made because of their similar location to the tropics, the author's understanding of at least one of the official languages of both countries and to encourage collaboration between the two continents. However, as the selection of the countries is based on the judgment of the researcher, there could be more countries that can complement the research by having more experience in applying sustainable practices and digital technologies in the rice sector.

There is also a limitation in choosing to investigate only rice cultivation and on-farm production due to the lack of time to assess the impact of food loss in different food supply chains. However, rice was chosen because it is a staple food for more than half of the world's population, considered a key source of nutrients as well as labor and income.

Another limitation is the lack of measurement of food loss in the countries and also the lack of standardization of the indicators found to compare both cases. For this reason, an additional assessment was made by analyzing land use with the indicator of tree cover loss, water use with two indicators, internal renewable flows of freshwater resources and annual freshwater withdrawals; and rice production, with three indicators, production in tons, yield and harvested area. To conduct research on food loss, it is necessary to know where in the supply chain it occurs, in which products and what environmental footprint is affected (FAO, 2019).

There is also a limitation due to the influence of author bias in the analysis of the interviews and the selection of interviewees. Nevertheless, the information acquired in the interviews is validated with the secondary data collected. As for the selection of interviewees, they were chosen from three different sectors and each organization interacts with different stakeholders, thus showing three different perspectives that complement the research.

The last limitation noted is that the research was conducted entirely with information found online, including analysis of documentary data but also additional information acquired from interviews. This is a limitation, as there may be practices that are only known in the field. However, both Colombia and Kenya have a lot of information on their websites and reports from different organizations have been found.

7.2 Future research

More research on food loss conducted closer to the farmer is needed to show what methods are implemented to measure it and to understand what constraints farmers have in tracking their food throughout the supply chain. This is in order to measure how the application of sustainable practices and digital technologies reduce food loss and what economic, social and environmental effects they have. In addition, more research is needed in different crops, in the case of Colombia in fruits and vegetables and roots and tubers mainly. Moreover, the role of external shocks (e.g. COVID-19, the Russia-Ukraine conflict and the triple planetary crisis) on agricultural production in Colombia should be investigated to understand how they affect different food supply chains and what practices should be prioritized to control negative impacts.

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APPENDICES

Appendix 1: Rice Production in Colombia

Country	*Year*	*Element*	*Unit: hectare*	*Value*	*Element*	*Unit: hectogram per hectare*	*Value*	*Element*	*Unit: tons*	*Value*
Colombia	2000	Area harvested	ha	472,759.00	Yield	hg/ha	47,324.00	Production	tons	2,237,270.00
Colombia	2001	Area harvested	ha	474,205.00	Yield	hg/ha	45,472.00	Production	tons	2,156,310.00
Colombia	2002	Area harvested	ha	429,790.00	Yield	hg/ha	48,001.00	Production	tons	2,063,030.00
Colombia	2003	Area harvested	ha	498,023.00	Yield	hg/ha	48,536.00	Production	tons	2,417,190.00
Colombia	2004	Area harvested	ha	519,736.00	Yield	hg/ha	48,038.00	Production	tons	2,496,720.00
Colombia	2005	Area harvested	ha	456,005.00	Yield	hg/ha	48,388.00	Production	tons	2,206,512.00
Colombia	2006	Area harvested	ha	429,911.00	Yield	hg/ha	45,717.00	Production	tons	1,965,414.00
Colombia	2007	Area harvested	ha	431,898.00	Yield	hg/ha	49,020.00	Production	tons	2,117,165.00
Colombia	2008	Area harvested	ha	493,554.00	Yield	hg/ha	48,887.00	Production	tons	2,412,852.00
Colombia	2009	Area harvested	ha	528,138.00	Yield	hg/ha	46,956.00	Production	tons	2,479,921.00
Colombia	2010	Area harvested	ha	482,297.00	Yield	hg/ha	41,223.00	Production	tons	1,988,191.00
Colombia	2011	Area harvested	ha	507,709.00	Yield	hg/ha	39,589.00	Production	tons	2,009,945.00
Colombia	2012	Area harvested	ha	482,198.00	Yield	hg/ha	48,066.00	Production	tons	2,317,710.00
Colombia	2013	Area harvested	ha	520,337.00	Yield	hg/ha	38,371.00	Production	tons	1,996,580.00
Colombia	2014	Area harvested	ha	461,273.00	Yield	hg/ha	47,836.00	Production	tons	2,206,525.00
Colombia	2015	Area harvested	ha	510,897.00	Yield	hg/ha	48,709.00	Production	tons	2,488,519.00
Colombia	2016	Area harvested	ha	570,432.00	Yield	hg/ha	53,630.00	Production	tons	3,059,204.00
Colombia	2017	Area harvested	ha	597,255.00	Yield	hg/ha	55,135.00	Production	tons	3,292,983.00
Colombia	2018	Area harvested	ha	526,668.00	Yield	hg/ha	55,915.00	Production	tons	2,944,860.00
Colombia	2019	Area harvested	ha	531,158.00	Yield	hg/ha	56,712.00	Production	tons	3,012,311.00
Colombia	2020	Area harvested	ha	596,415.00	Yield	hg/ha	57,412.00	Production	tons	3,424,119.00
Colombia	2021	Area harvested	ha	544,635.00	Yield	hg/ha	61,078.00	Production	tons	3,326,528.95

Appendix 2: Rice Production in Kenya

Country	*Year*	*Element*	*Unit: hectare*	*Value*	*Element*	*Unit: hectogram per hectare*	*Value*	*Element*	*Uni: tons*	*Value*
Kenya	*2000*	*Area harvested*	*ha*	*13,882.00*	*Yield*	*hg/ha*	*37,710.00*	*Production*	*tons*	*52,349.00*
Kenya	*2001*	*Area harvested*	*ha*	*13,200.00*	*Yield*	*hg/ha*	*34,091.00*	*Production*	*tons*	*45,000.00*
Kenya	*2002*	*Area harvested*	*ha*	*13,000.00*	*Yield*	*hg/ha*	*34,615.00*	*Production*	*tons*	*45,000.00*
Kenya	*2003*	*Area harvested*	*ha*	*10,781.00*	*Yield*	*hg/ha*	*37,568.00*	*Production*	*tons*	*40,502.00*
Kenya	*2004*	*Area harvested*	*ha*	*13,223.00*	*Yield*	*hg/ha*	*37,280.00*	*Production*	*tons*	*49,295.00*
Kenya	*2005*	*Area harvested*	*ha*	*15,940.00*	*Yield*	*hg/ha*	*39,321.00*	*Production*	*tons*	*62,677.00*
Kenya	*2006*	*Area harvested*	*ha*	*23,106.00*	*Yield*	*hg/ha*	*28,062.00*	*Production*	*tons*	*64,840.00*
Kenya	*2007*	*Area harvested*	*ha*	*16,457.00*	*Yield*	*hg/ha*	*28,715.00*	*Production*	*tons*	*47,256.00*
Kenya	*2008*	*Area harvested*	*ha*	*16,734.00*	*Yield*	*hg/ha*	*13,076.00*	*Production*	*tons*	*21,881.00*
Kenya	*2009*	*Area harvested*	*ha*	*21,829.00*	*Yield*	*hg/ha*	*19,333.00*	*Production*	*tons*	*42,202.00*
Kenya	*2010*	*Area harvested*	*ha*	*20,181.00*	*Yield*	*hg/ha*	*42,384.00*	*Production*	*tons*	*85,536.00*
Kenya	*2011*	*Area harvested*	*ha*	*28,034.00*	*Yield*	*hg/ha*	*39,676.00*	*Production*	*tons*	*111,229.00*
Kenya	*2012*	*Area harvested*	*ha*	*29,630.00*	*Yield*	*hg/ha*	*46,643.00*	*Production*	*tons*	*138,204.00*
Kenya	*2013*	*Area harvested*	*ha*	*31,349.00*	*Yield*	*hg/ha*	*39,955.00*	*Production*	*tons*	*125,256.00*
Kenya	*2014*	*Area harvested*	*ha*	*28,390.00*	*Yield*	*hg/ha*	*39,543.00*	*Production*	*tons*	*112,263.00*
Kenya	*2015*	*Area harvested*	*ha*	*29,438.00*	*Yield*	*hg/ha*	*39,566.00*	*Production*	*tons*	*116,473.00*
Kenya	*2016*	*Area harvested*	*ha*	*29,337.00*	*Yield*	*hg/ha*	*34,601.00*	*Production*	*tons*	*101,510.00*
Kenya	*2017*	*Area harvested*	*ha*	*30,392.00*	*Yield*	*hg/ha*	*26,717.00*	*Production*	*tons*	*81,198.00*
Kenya	*2018*	*Area harvested*	*ha*	*25,966.00*	*Yield*	*hg/ha*	*43,366.00*	*Production*	*tons*	*112,605.00*
Kenya	*2019*	*Area harvested*	*ha*	*24,992.00*	*Yield*	*hg/ha*	*64,255.00*	*Production*	*tons*	*160,585.00*
Kenya	*2020*	*Area harvested*	*ha*	*28,276.00*	*Yield*	*hg/ha*	*63,973.00*	*Production*	*tons*	*180,890.00*
Kenya	*2021*	*Area harvested*	*ha*	*25,548.00*	*Yield*	*hg/ha*	*72,804.00*	*Production*	*tons*	*186,000.00*

Appendix 3: Sustainable Agricultural Practices in Colombia

Year	*On-farm activity*	*Product*	*Place*	*Problem*	*Sustainable Agricultural Practice*	*Economic Impact*	*Social Impact*	*Enviromental Impact*	*Source*
2002	Harvest	Rice	Boyacá Tolima	Rice requires for its nutrition high amounts of nitrogen, phosphorus and potassium, which in tropical and intertropical agriculture are of very low efficiency	Biofertilizers	Improving productivity and production competitiveness, while reducing costs	False belief that the application of biological inputs is related to artisanal production and that composting of organic waste replaces the use of formulated products that ensure sustainable production	Reduced impact on the environment by reducing chemical fertilization without detriment to yields	(Sanjuán Pinilla & Moreno Sarmiento, 2010); (Castilla Lozano & Tirado Ospina, 2022)
2009 and 2015	Harvest		Tolima	Large volumes of water are required to produce rice	System of rice intensification (SRI)	Increasing yields, reducing seed and water costs, harvesting earlier, reducing rice losses due to pest and disease attack; but it involves high cost of labor	Shortage of people to work as it is heavy work but improve farmers' water management	Efficient use of natural resources such as water and land, as well as the implementation of organic fertilizers resulting in the reduction of chemicals in the soil and the reduction of GHG	(Acosta Buitrago, 2011); (Witkoski, 2017)
2012	Pre-harvest		Caribe Humedo Caribe Seco Llanos Centro	Reduced crop yields due to adverse weather conditions combined with lower rice prices due to the free trade agreement with the United States	Crop rotation	Improving flexibility in planting seasons and lowering costs per ton per year	Improving adaptation to new economic and climatic conditions	Breaking the reproductive cycle of some pests, improving soil fertility, using less water and reduce weed infestation in the field	(Fedearroz, 2012)
	Harvest			High fertilizer costs for rice cultivation as well as the wasteful use of crop residues.	Agricultural residues and compost for soil fertilization	Increasing fertilization efficiency due to carbon and potassium gain, as well as increasing crop profitability	Improving farmers' livelihoods	Utilization of nutrients from agricultural residues in rice cultivation, while reducing soil chemicals and GHG emissions	(Castilla Lozano, 2012)
2014	Pre-harvest Harvest Post-harvest	Rice Cassava Beans Potato	Córdoba	Reduction in annual rice production yields due to climate change	Stakeholders project	Rice growers avoid massive production losses	Research conducted between a team of young scientists and the rice association (FEDEARROZ), in which farmers participated by collecting and sharing information on their farming practices	Prediction of a drought in the region that would lead to losses due to climate change	(CCAFS, 2016)
2016	Harvest	Rice	Tolima Norte de Santander Córdoba Cesar Casanare	High CO2 emissions and water consumption in rice production, generating water availability problems	Alternative Wetting and Drying (AWD)	Increasing productivity and farmer income	Improving adaptation and resilience to climate change	Reducing water inputs and decreases methane emissions.	(Chirinda et al., 2017); (Chirinda et al., 2018)
2016		Rice	Caribe Humedo Caribe Seco Llanos Centro	Reduction in annual rice yields due to lack of nutrients in the soil	Recommended rates of fertilizers	Increases crop nutrition efficiency	Tailor-made solution for each rice region of the country according to its own requirements.	Reduction of chemicals in the soil and excess of fertilizers	(Castilla Lozano et al., 2018)

Appendix 4: Sustainable Agricultural Practices in Kenya

Year	*On-farm activity*	*Product*	*Place*	*Problem*	*Sustainable Agricultural Practice*	*Economic Impact*	*Social Impact*	*Enviromental Impact*	*Source*
2005	Pre-harvest	Rice	Mwea	Degradation of soil structure due to farming practices	Conservation tillage	Decreases income but also fertilizer and irrigation costs as the soil recovers	Improving climate change adaptation	Natural soil recovery	(Indeche & Ondieki-Mwaura, 2016); (NEMA, 2013)
2009	Harvest		Mwea Kirinyaga	Problems with water availability due to limited resources, as well as problems with crop yield.	System of Rice Intensification (SRI) in an irrigation system	Better yield and productivity results in the crop	Improving farmers' livelihoods and water use efficiency	Improving the whole mechanism of plant food production (in leaves and roots) and save irrigation water through soil aeration and better phenotypic expression	(Nyamai et al., 2012); (Ndiiri et al., 2013); (Ndiiri et al., 2017); (Kadipo et al., 2021); (Mbatha et al., 2019) ; (Tadele, 2017)
			Mwea	Problems with water availability due to limited resources	Alternative Wetting and Drying (AWD) in an irrigation system	Increasing crop yield with an intermittent irrigation program	Improving climate change adaptation	Adaptation to the condition of water scarcity and GHG reduction	(Nyamai et al., 2012)
2013	Pre-harvest		Kirinyaga Embu Mberee	Low production due to lack of knowledge about the best combination of physical and climatic factors for rice production	Land suitability analysis: Multi-Criteria Evaluation (MCE) & GIS approach	Optimization of rice production to reduce imports and become self-sufficient with local production	Improving adaptation to climate change and improving farmers' livelihoods	Achieving optimal utilization of available land resources	(Kihoro et al., 2013)
2015	Pre-harvest Harvest Post-harvest		Mwea	Crop pests and diseases	Timing harvesting	Reducing the possibility of crop losses	Practice carried out due to the experience of the farmer himself and by the community of farmers in the area.	Maintain good soil structure for higher crop yields	(Indeche & Ondieki-Mwaura, 2015)
				Lack of nutrients for plant growth and good soil structure and texture	Use organic manure	Cost reduction by reducing the use of inorganic fertilizers, although the organic product is expensive	Practice carried out due to the experience of the farmer and his community	Prevents soil degradation with inorganic fertilizers with long-term effect	(Indeche & Ondieki-Mwaura, 2015); (Indeche & Ondieki-Mwaura, 2016)
	Harvest			Water scarcity due to unforeseen weather changes	Protection of water quality and quantity	Reduction of crop irrigation costs	Improving climate change adaptation	Improving water management	(Indeche & Ondieki-Mwaura, 2015); (Indeche & Ondieki-Mwaura, 2016)
	Pre-harvest			Lack of soil nutrients and weed risks in crops	Leave land fallow	Piece of land that is not used for harvesting but reduces fertilizer and irrigation costs because nutrients are allowed to recover	Improving climate change adaptation	Natural soil recovery	(Indeche & Ondieki-Mwaura, 2015)
	Post-harvest			Lack of soil nutrients	Retain crop residues	Cost reduction by reducing the use of inorganic fertilizers	Discouragement of implementation due to theft because it can be sold to livestock farmers	Natural recovery of the soil and prevention of soil degradation	(Indeche & Ondieki-Mwaura, 2015); (Indeche & Ondieki-Mwaura, 2016)
	Pre-harvest			Lack of nutrients for a fertile soil and risk of suffering from rice blast disease or weed in the crop	Crop rotation	Significantly reduces the risk of crop failure	Risk aversion so maintaining the control strategies of own and other farmers' experience	Natural recovery of the soil and prevention of soil degradation	(Indeche & Ondieki-Mwaura, 2015); (Indeche & Ondieki-Mwaura, 2016); (Tadele, 2017)
	Harvest			Weeds cause growth suppression and yield reduction through competition for light, nutrients, water, space with rice production	Integrated pest management	Low-cost activities that are within the farmer's reach to reduce the risk of pests in production while increasing crop yield	Maintaining the control strategies of own and other farmers' experience and improving climate change adaptation	Minimize potential detrimental impacts to the environment	(Indeche & Ondieki-Mwaura, 2015); (Indeche & Ondieki-Mwaura, 2016); (Fahad et al., 2020)
				Risk of suffering from rice blast disease in the crop	Recommended rates of fertilizers	Cost reduction by reducing the overuse of fertilizers	Risk aversion so maintaining the control strategies of own and other farmers' experience	Reducing inputs such as chemicals and excess fertilizers in the soil	(Indeche & Ondieki-Mwaura, 2015); (Indeche & Ondieki-Mwaura, 2016)
	Pre-harvest Post-harvest			Lack of nutrients for plant growth and good soil structure and texture	Use green manure	Cost reduction by reducing the use of inorganic fertilizers	Lack of motivation to produce rice differently due to middlemen and low rice prices	Planting a fast-growing legume crop and plowing it to provide the soil with nutrients for the next crop.	(Indeche & Ondieki-Mwaura, 2015); (Indeche & Ondieki-Mwaura, 2016)
	Pre-harvest Harvest Post-harvest			Inefficient management of crop residues and high cost of imported inorganic fertilizers	Rice husk as organic fertilizer	Increasing crop yields with an affordable fertilizer	Improving farmers' livelihoods	Reducing agricultural waste and soil acidity	(Tadele, 2017); (Cardiff & Meyer, 2018)
2017	Pre-harvest			Degradation of soil structure and lack of nutrients for a fertile soil	Intercropping	Increasing the amount of harvest	Diet diversifies and provides a cheaper source of protein using legumes	Improving soil fertility because legumes add nitrogen to the soil and reduce soil erosion due to the vegetative cover of the soil	(Tadele, 2017); (Ogutu et la., 2012)
	Harvest	Maize Rice	Kenya	Crop pests and diseases	Push and Pull system for pest control	Cost reduction by reducing the use of pesticides and increasing crop yield	Acceptance by farmers in the implementation of the system	Reducing the amount of pesticide application in the soil	(Tadele, 2017); (ICIPE, 2015)

Appendix 5: Digital Agricultural Technologies in Colombia

Year	*On-farm activity*	*Product*	*Place*	*Problem*	*Technology*	*Solution*	*Source*
2012	Harvest	Rice	Tolima	Loss of applied nutrients due to inadequate soil moisture	Baro-Diver: datalogger eTape: liquid level sensor	Measurement and quantification of water entering rice fields for decision making	(Castilla Lozano & Tirado Ospina, 2022)
	Pre-harvest Harvest			Decision making based on the visual observation of the moment to fertilize a crop when it is chlorotic, which causes losses in the production potential of the variety planted	Chlorophyllometer or the Soil Plant Analysis Development (SPAD)	It estimates indirectly, quickly and without tissue destruction, the content of chlorophyll and nitrogen in the leaves of different crops, to determine the opportune moments of application of fertilizers, especially nitrogen,	(Castilla Lozano & Tirado Ospina, 2022)
	Harvest		Caribe Humedo Caribe Seco Llanos Centro	Constant soil changes due to climate and agricultural practices	Vibrating chisel ploughs	Improving water infiltration in compacted soils, allowing a deep tillage operation and breaking up hard layers while leaving the top layer. This improves soil structure.	(Alwarritzi et al., 2020); (Pineda Suarez, 2021); (Guzmán García et al., 2018); (DANE & FEDEARROZ, 2018)
				Constant soil changes due to climate and agricultural practices, as well as inadequate water management in hard-to-reach areas	Land plane levelers	Connected to the tractor, it is used to eliminate, in a superficial way, the irregularities and unevenness in the ground caused by the previous production. The objective is to increase efficiency in downstream works, such as reducing runoff water losses.	(Alwarritzi et al., 2020); (Pineda Suarez, 2021); (Guzmán García et al., 2018); (DANE & FEDEARROZ, 2018)
				Constant soil changes due to climate and agricultural practices, as well as inadequate water management in hard-to-reach areas	Tapia	Connected to the tractor, it is used to build the ridges that divide the lot into plots and retain the water for the development of the crop. It improves the efficiency of water distribution in the rice field.	(Alwarritzi et al., 2020); (Pineda Suarez, 2021); (Guzmán García et al., 2018); (DANE & FEDEARROZ, 2018)
	Pre-harvest			Crop losses due to lack of monitoring of the nutritional and phytosanitary status of the crop	Pre-fertilization	Application of basal fertilizers to know the soil physiology and to be able to manage weeds in a timely manner.	(Alwarritzi et al., 2020); (DANE & FEDEARROZ, 2018)
	Pre-harvest			Germination problems due to lack of high quality seeds, decreasing yields in planted lots	Certified seeds	Adequate establishment and uniformity in germination, which allows performing fundamental tasks efficiently, such as weed control and fertilization.	(Alwarritzi et al., 2020); (DANE & FEDEARROZ, 2018); (Guzmán et al., 2018)
	Harvest			Crop losses due to lack of monitoring of the nutritional and phytosanitary status of the crop	Drill sowing	It is used to control weeds and for the application of agrochemicals with ground equipment.	(Alwarritzi et al., 2020); (DANE & FEDEARROZ, 2018)
	Pre-harvest Harvest			Losses due to lack of crop yield control	Sowing density less than 150 kg/hectare	Requirement to achieve a good crop yield, depending on the optimum plant population, i.e. meets the minimum number of plants per unit area that guarantees a high yield.	(Alwarritzi et al., 2020); (DANE & FEDEARROZ, 2018)
	Harvest			Loss of applied nutrients due to inadequate soil moisture	Continuous irrigation	Intermittent application of water at 3-5 day intervals at the top of the plot to fill the end of the plot.	(Alwarritzi et al., 2020); (DANE & FEDEARROZ, 2018)
2014	Pre-harvest Harvest		Córdoba	Lack of tools to collect and share information on farming practices to receive advice	Mobile app	Through the application, farmers collect and share information about their farming practices	(CCAFS, 2016)
	Pre-harvest Harvest Post-harvest			Reduction in annual rice production yields due to climate change	Big Data analysis	Analysis of crop monitoring data, weather data and seasonal forecasts to provide farmers with best practices	(CCAFS, 2016); (Gil, 2016)
	Harvest		Caribe Humedo Caribe Seco Llanos Centro	Reduction in annual rice yields due to lack of nutrients in the soil	Digital platform - Rice Fertilizer System	Tool that provides personalized recommendations on the fertilizers to be applied to the crop according to the requirements of each place considering the geographical location and history, since it stores geo-referenced information of the lots.	(Castilla Lozano & Tirado Ospina, 2022); (Castilla Lozano et al., 2018)
2015	Harvest		Huila	Low agricultural production and wasteful use of natural resources	Remote monitoring of irrigation systems	Monitoring of different variables (water flow, temperature and magnetic state of the pump motor) in the rice crop, then recording, processing and tabulating the information in a computer system and sending it in real time via the Internet to the end user	(Quintero et al., 2016)

2016	Harvest		Tolima	Areas of difficult access to irrigation that cannot be prioritized	Time-Domain Reflectometry (TDR): detect location	Builds moisture maps to identify areas with higher and lower moisture retention and prioritize areas that are difficult to access for irrigation	(Castilla Lozano & Tirado Ospina, 2022) (Pineda Suarez, 2021); (Pineda, 2016); (Ortiz Londoño et al., 2020)
	Pre-harvest Harvest Post-harvest		Tolima Norte de Santander Córdoba Cesar Casanare	Lack of high-resolution maps to understand soil variability according to biophysical properties due to the large amount of soil data	Digital soil mapping (DSM)	Application of available data combined with less intensive field sampling to create cost-effective, high-resolution soil maps.	(Chirinda et al., 2017)
	Harvest			High CO_2 emissions and water consumption in production, which generates water availability problems	Alternate Wetting and Drying (AWD)	Intermittent irrigation program that alternates flooded and non-flooded conditions, which reduces water inputs and decreases methane emissions.	(Chirinda et al., 2017); (Chirinda et al., 2018); (Pineda, 2016)
	Pre-harvest Harvest		Caribe Humedo Caribe Seco Llanos Centro	Reduction in annual rice yields due to lack of soil nutrients and soil erosion	Web management system - SIFA web: rice fertilization platform	Support tool that gathers all the necessary instruments for the control and good management of soil fertilization, generating personalized fertilization recommendations to farmers	(Castilla Lozano et al., 2018)
2017	Harvest		Tolima Huila	Inadequate water management in hard-to-reach areas	Multiple Inlet Rice Irrigation (MIRI)	A system of conduction and distribution of irrigation water through multiple inlets, which are inserted along the hose. They regulate the water flow through their manual opening and closing system.	(Castilla Lozano & Tirado Ospina, 2022); (Pineda Suarez, 2021); (Guzmán C. et al., 2018); (Pineda, 2016)
				Inadequate water management in hard-to-reach areas	Real Time Kinematic (RTK)	Tool that allows the elaboration of digital elevation maps in real time for the implementation of irrigation designs with a high degree of accuracy based on the topography of the terrain. It generates corrected kinematics in real time to increase irrigation efficiency.	(Pineda Suarez, 2021); (Guzmán C. et al., 2018)
	Pre-harvest		Caribe Humedo Caribe Seco Llanos Centro	Lack of knowledge of farmers about weather forecasting, as well as good agricultural practices and sustainable management	Mobile app - Planea tu cultivo: crop planning	Farmers get better information for crop planning throughout the year, real-time weather and crop information is analyzed and collected, and indicates the best time to plant	(Popescu, 2017)
2019	Pre-harvest Harvest Post-harvest			Climatic conditions have a marked influence on plant response to applied nutrients.	Digital platform - ¿Va a llover? Climate service platform	Allowing to know the historical climate of the region, agro-climatic forecasts, and weather conditions in real time	(Castilla Lozano & Tirado Ospina, 2022)
2020			Tolima	Incorrect decision making due to not being able to visualize the yield of a crop because of difficult access	Satellite images by the Normalized Vegetation Index (NDVI)	Mapping tool through the analysis of historical information from satellite images of each lot, where the temporal and spatial variability of the terrain is determined	(Castilla Lozano & Tirado Ospina, 2022); (Guzmán C. et al., 2018) ; (Ortiz Londoño et al., 2020)
	Harvest			Losses due to lack of crop yield control	Sensors and global positioning system (GPS) installed on the harvester	Making a spatial representation of real-time yield data during crop harvesting	(Castilla Lozano & Tirado Ospina, 2022); (Guzmán C. et al., 2018); (Ortiz Londoño et al., 2020)
	Pre-harvest Harvest Post-harvest			Loss of applied nutrients due to inadequate water management, and crop losses due to lack of monitoring of the nutritional and phytosanitary status of the crop in areas with difficult access	Drones	They carry different measuring cameras (thermographic, multispectral, LIDAR, optical) to capture images that allow the calculation of indices such as NDVI, as well as the creation of sectorized maps with the indices. They also monitor the nutritional, phytosanitary and water status of the crop	(Castilla Lozano & Tirado Ospina, 2022); (Guzmán C. et al., 2018)
	Harvest			Incorrect seed placement for lack of control and knowledge of the crop	Sowing monitors	Define the amount of seed that should be spread in a specific region by combining the variety, seed outflow, and working speed, resulting in a seeding map with the amount of seed supplied at each reference point	(Guzmán C. et al., 2018)
2022	Pre-harvest Harvest Post-harvest		Caribe Humedo Caribe Seco Llanos Centro	Lack of financial inclusion (access to credit, subsidies, incentives or state support) for smallholder farmers	Digital platform - Mi registro rural: digital citizen services	Increased efficiency in the management of documentation, reduction of document processing cycles, immediate communication of projects, programs and incentives offered by sector entities to farmers	(Fedearroz, 2022)

Appendix 6: Digital Agricultural Technologies in Kenya

Year	*On-farm activity*	*Product*	*Place*	*Problem*	*Technology*	*Solution*	*Source*
2011	Harvest	Different crops	Nairobi Thika Mutithi Machakos Mitunguu Matanya Nakuru Eldoret	Low crop productivity due to lack of access to water	Solar-Powered Irrigation System - SunCulture: uses off-grid solar technology to provide small farms with reliable access to water, irrigation, lighting and mobile charging within a single system.	Farmers increase their income by producing more, while decreasing the amount of water needed to grow the crop and also the waste in runoff.	(Osiemo et al., 2021); (Sunculture, 2022)
2012	Pre-harvest Harvest Post-harvest	Different crops	Thika	Lack of communication on prices, agricultural practices and seedling availability, which has a negative impact on production and product quality	Digital platform - Connected Farmer Alliance: commercial mobile agriculture (mAgri) solution that improves the efficiency of both agribusinesses and the smallholder farmers that supply them by addressing inefficiencies in value chain management	Increasing the productivity and profitability of smallholder farmers by improving their communication with supply chain stakeholders	(Moceviciute & Babcock, 2016); (Ujuzikilimo, 2021)
2015		Different crops	Kenya	Farmers are facing an increasingly volatile climate due to climate change, leading to more frequent extreme weather events	Digital platform - Start-up UjuziKilimo: building sensors and agricultural data analysis tools to enable the collection and analysis of agricultural data, as well as to give meaning to the data so that smallholder farmers can make accurate decisions about their crops	Helping farmers to make sound crop decisions by providing accurate information	(Osiemo et al., 2021); (Ujuzikilimo, 2021)
2016		Different crops	Kenya	Farmers with low productivity due to adverse weather and soil erosion, generating the need to look for more resilient and environmentally friendly practices.	Mobile App - CropHQ: farm advisory application that provides farmers with satellite photos, weather data, crop analysis, drone imagery for monitoring crop conditions, and a community interaction page.	Increase the productivity and profitability of smallholder farmers by giving them the right information about their crops so they can make good decisions, and improve communication with stakeholders in the supply chain to avoid losses.	(Osiemo et al., 2021); (Njirani, 2021)
		Different crops	Nairobi Kenya	Farmers lack access to credit and therefore cannot afford the cost of high-yield investments such as hybrid seeds and fertilizers. In addition, smallholder farmers live in rural, remote and difficult to access locations.	Digital platform - Start-up Apollo Agriculture: uses satellite data and machine learning to improve the productivity of small farms through an agricultural platform that includes advice, insurance, agricultural products and financing	Accessing to high-quality agricultural inputs and advice to make decisions that increase crop productivity	(Osiemo et al., 2021); (Bosilkovski, 2020); (Kene-Okafor, 2020)
2017	Harvest	wheat maize potatoes coffee tea horticulture	Meru	Lack of knowledge on the part of farmers about the current state of the soil, which leads to incorrect decision-making	Mobile App - AgroCare: combining portable soil sensors with big data and analytics to provide accurate soil analysis	Providing customized fertilizer recommendations based on soil data acquired using a handheld scanner. Farmers apply fertilizers more efficiently, focusing on trouble areas and reducing waste while increasing outputs	(Krishnan et al., 2020); (AgroCares, 2020)
		Rice, cabbage, tomato, kale, capsicum, green beans, banana, coffee, maize, orange	Meru Nakuru Nanyuki Timau	Availability of water for irrigation, potential risk of pests, and low yields due to lack of nutrients in the soil	Drones - ThirdEye: establishing a network of flying sensor operators that are equipped with a high spatial resolution camera to capture the location of plants in need of watering. Water productivity is estimated by collecting satellite data and applying an algorithm	Assisting farmers in making decisions on the use of scarce resources such as water, seeds, fertilizers and labor, increasing water productivity and yield	(Krishnan et al., 2020); (De Klerk et al., 2019)
2019	Pre-harvest Harvest Post-harvest	Cereals Fruits Legumes Roots	Kenya	Farmers are facing an increasingly volatile climate due to climate change, leading to more frequent extreme weather events and environmental degradation	Kenya Agricultural Observatory Platform: integrated web platform that produces localized, real-time agro-advice for farmers and other stakeholders using geo-data from satellites	Providing adequate information to monitor and predict the current crop situation and make timely and accurate decisions	(Osiemo et al., 2021); (KALRO, 2021)

Appendix 7: Recommendations

On-farm activity	*Identified problem*	*Recommendations*	*Brief explanation*	*Benefits*
Harvest	Low productivity due to lack of access to water as rice crops require large amounts of water	System of Rice Intensification (SRI): rice productivity is increased by modifying plant, soil, water and nutrient management while minimizing external inputs such as fertilizers and pesticides	The practices consist of planting younger seedlings with wider spacing and intermittent irrigation, as well as implementing mechanical weeders and the use of organic material for fertilization for higher paddy rice yields and better crop intake	Increasing yields and earlier harvest Reducing seed and water costs Reducing chemicals in the soil and GHG emissions Reduced rice losses from pest and disease attacks Access to and sale of health food
Harvest	Changing climatic factors affect rice yields by causing crop damage, e.g., lack of soil moisture affects nutrient management and weed, pest and disease prevention	Push and Pull system for pest control: Intercropping system that ecologically controls pests and weeds.	The technology involves intercropping cereals with a pest repellent plant, which drives away or deters stemborers from the rice crop, while an attractant trap plant is placed around the perimeter of the intercrop to track and trap weeds and pests	Increasing crop yields and soil health Increasing soil nutrition by improving soil fertility Decreasing of chemical products such as pesticides Weed and pest control Soil moisture conservation
Harvest	Low crop yields due to lack of nutrients in the soil from previous agricultural practices	Intercropping: planting of two or more crops in the same growing season and on the same piece of land	Cropping system that combines legumes and cereals in the same field for food production	Reducing soil erosion due to the optimal plant coverage Increasing the amount of harvest Improving soil fertility Reducing dependence on chemical fertilizers
Pre-harvest	Low crop yields due to soil erosion from previous agricultural practices	Conservation tillage: farming method that consists of planting directly into the soil with minimal soil disturbance to maintain resources and environmental conditions stable	This is a method of land preparation that involves only making planting holes/farrows using a ripper and leaving the rest of the land unploughed	Improving soil fertility Soil erosion control Moisture conservacion Reducing fuel consumption
Harvest Post-harvest	Insufficient management of agricultural waste	Rice husks as fertilizer: collection of rice husks to be carbonized and converted into low-cost organic fertilizer	Rice husk residues from farmers are collected and converted into biochar, which is then preserved, processed and a local enzyme is added to allow microbial growth and turned into organic fertilizer	Reducing soil acidity Reducing the need for irrigation Improving crop yield Reducing $CO2$ emissions Additional income
Harvest	Farmers face periods of low rainfall affecting crop production, as well as droughts that reduce crop yields. There is also a loss of irrigation water due to leaks during long-distance transportation	Solar-Powered Irrigation System: an efficient technique to assist irrigate crops because it delivers water in small dosages directly to plant roots.	The components are a motor pump, a solar panel, a reservoir and an irrigation system. The solar panel provides electricity to a pump, the water reaches a reservoir where it is stored and, when released, flows into a drip irrigation system.	Reducing electricity costs Decreasing water waste Reducing soil erosion Improving yields Irrigation in remote areas
Pre-harvest Harvest	Farmers do not have access to soil testing services because there is no access to a reliable laboratory in the region, where they can identify the state of the soil to apply the right amount of fertilizers	Soil analysis system: the system provides customized fertilizer recommendations based on soil data acquired using a handheld scanner.	It combines a mobile app, portable soil sensors, big data analytics and machine learning to provide accurate soil analysis. Scanner: determining the chemical composition of soils. Lad-in-a-box: producing a spectral image of the sample analyzed by the database Mobile App: checking in real-time the nutrients in the soil sample	Applying fertilizers more efficiently Soil mapping Reducing waste Increasing output
Pre-harvest Harvest Post-harvest	Lack of communication on prices, agricultural practices and seedling availability, which has a negative impact on production and product quality	Digital platform: it improves the efficiency of both agribusinesses and the smallholder farmers that supply them by addressing inefficiencies in value chain management	The digital platform enables mobile payments, direct communication between a farm business and its smallholder farmers, and business data collection and analysis	Improving communication with buyers Increasing productivity and profitability Reducing food loss
Pre-harvest Harvest Post-harvest	Low productivity of farmers due to adverse weather conditions and economic factors such as difficult access to credit, not being possible to make high investments in seeds or fertilizers	Digital platform: it uses satellite data and machine learning to improve smallholder farmers productivity	The platform's services include advice, insurance, high-quality agricultural products and financing. It creates credit profiles for smallholder farmers using machine learning models. It performs identification checks on farmers and takes satellite coordinates of their fields	Accessing to high-quality agricultural inputs Increasing crop productivity Crop advisory services
Harvest	Low productivity due to adverse weather conditions and soil erosion, which makes it necessary to look for more resistant and environmentally friendly practices	Mobile application: it functions as an advisory tool for farmers, including satellite photography, weather data, crop analysis, and a community engagement page	Farmers have access to weekly farm reports, crop analysis, localized weather reports, pest and disease scouting platform, profit and loss projections, records management, drone-based satellite imagery for crop monitoring, and a farmer community page to connect with buyers when crops are ready for harvest	Increasing crop productivity and profitability Improving communication with stakeholders Reducing food loss

Appendix 8: Interview guideline

Interview guideline

Organization name:
Interviewee name:
Interviewee position:

Good morning/afternoon, I hope you have a nice day. My name is Maria Atehortua. I am a master's student in Sustainable Development, Management and Policy at MODUL University Vienna. I am writing my master thesis and this interview will serve as a validation part of my research. The topic of my thesis is the role of digitalization on the way to sustainable practices in the agricultural sector in Colombia with the aim to reduce food loss – focused on the rice product.

The interview will last approximately 45 minutes. I will ask you general questions about food loss, digital agricultural technologies and sustainable land practices and afterward, I will show you the recommendations I have proposed to improve agricultural practices.

Do you have any questions? If not, I would like to start the interview.

Informed consent:

The interview has entirely academic purposes, therefore I would like to know if you consent to the recording of the interview, as well as the use of the data to be mentioned for later analysis. It should be noted that the information obtained will only be used in this master's thesis. Upon request, responses can be anonymous and the privacy of respondents is guaranteed.

Part I – General topics:

Identify knowledge about food loss in the agricultural sector in Colombia, as well as sustainable agricultural practices and digital agricultural technologies that have been implemented.

Please provide some insights from your perspective on these issues.

Food loss is a global problem that generates economic, social and environmental consequences. It is considered the decrease in the quantity or quality of food along the food supply chain and occurs from harvest/slaughter/catch up to, but not including, the retail level (FAO, 2019), i.e., it mainly involves on-farm activities.

- Question 1: According to the studies and projects carried out in the organization you work for; do you consider food loss in Colombia to be a problem? Please specify.
- Question 2: What do you consider to be the main causes of food loss in Colombia? Is there any project in your organization currently in the phase of implementation to tackle these causes?
- Would you like to add or comment on anything else you consider important on the above topic?

Sustainable agriculture must meet the food needs of present and future generations while ensuring profitability, environmental health and social and economic equity. This requires significant improvements in production efficiency to reduce the use of natural resources and greenhouse gas emissions. According to FAO, sustainable agricultural practices must make full use of technology, research and development, but with much greater integration of local knowledge. This requires stakeholders to work together in new and stronger partnerships.

- Question 3: How would you describe the status of sustainable agricultural practices in Colombia?

1 2 3 4 5 6 7 8 9 10

Early state Quite elaborated Very advanced

- Question 4: What are the obstacles faced by Colombia in the implementation of sustainable practices in the agricultural sector?
- Question 5: Are there any projects your organization is undertaking to assist farmers in implementing sustainable agricultural practices?
- Would you like to add or comment on anything else you consider important on the above topic?

Digitalization in agriculture is known as a new alternative to provide solutions to the global food problem while reducing its impact on the environment and maintaining economic income (Lioutas et al., 2021). According to the United Nations (2017) definition, "digital agriculture is the use of new and advanced technologies, integrated into a system, to enable farmers and other stakeholders within the agricultural value chain to improve food production" (United Nations, 2017).

- Question 6: Are digital technologies a key aspect in the implementation of sustainable agricultural practices in Colombia? And if so, is the country's digital infrastructure ready for such a transformation?
- Question 7: What are the obstacles faced by Colombia in the implementation of digital technologies in the agricultural sector?
- Question 8: Are there any projects your organization is undertaking to help farmers apply digital agricultural technologies?
- Would you like to add or comment on anything else you consider important on the above topic?

Part II – Recommendations

The adaptation of different agricultural practices depends on different local conditions such as soil, climate, culture, and socioeconomic conditions, therefore, it is necessary to evaluate their potential to function in Colombia's current conditions.

As part of the research, I have developed 10 recommendations that I would like to show you.

(See Appendix 7).

I would like to have your perspective to validate which recommendations are applicable to rice production in Colombia to generate more sustainable agricultural practices in order to reduce food loss.

Appendix 9: Coding of expert interviews

FOOD LOSS							
According to the studies and projects carried out in the organization you work for; do you consider food loss in Colombia to be a problem? Please specify.	If the problem of food loss is tackled, a third of the food is gained and food production would be more efficient.	There is a loss of food and it is estimated to be between 20 - 25% (8 to 10 million tons of food) in production according to national statistics.	There is a loss of food due to lack of infrastructure to store water and store the harvest, the latter is a bottleneck because after harvesting, the rice has to be dried immediately, if it is not dried in less than 24 hours, the production is lost.	It is a very important issue for the country; it is known that throughout the production chain there are losses but there is no awareness of the consequences that this is causing, so it is not known which way it could be oriented to avoid it.	According to a national planning study, it is determined that of the total food supply, one-third or 34% is lost, so it is certain that there is a significant loss of food.	There is a loss of food in Colombia due to many deficiencies along the supply chain. In the domestic market there is a breakdown due to the lack of planning of crop and harvest cycles with the markets.	Rice is a perishable product, so if it is not given the right conditions at the time of harvesting and commercialization, losses begin to occur.
What do you consider to be the main causes of food loss in Colombia?	The expansion of the agricultural frontier to increase production generates more deforestation and increases malnutrition because production is not made more efficient. Accelerated transformation of food systems without considering ecosystem security and food safety Effects of cimate change	Authorities do not support the national agriculture due to imports and exports; they don't have interest in the development of industrialized processes. Related to adverse weather effects, prolonged winters, flooding of the growing areas and droughts that prevent the fruit from ripening. Producers do not have good conditions for production on the farm, there are road deficiencies and prices are very low, causing producers to lose incentives to harvest. There is no connection between the land available for agriculture and the economic cycles of the country. Agricultural producers do not have the capacity to develop a large production because they do not have good credit and price guarantees that allow them to make an investment with the possibility of recovering it and making a profit. The pandemic and the war between Russia and Ukraine increased the prices of agricultural inputs and products.	The lack of infrastructure for water storage and crop storage Price instability does not allow for long-term decision making Farmers usually have a low level of education People from the countryside are moving to the city, especially young people, and the countryside is becoming lonely	The variability of prices, when the prices of agricultural products are low, there is a high food loss because producers prefer not to harvest the crop, but leave it in the ground and turn it over for the next harvest, so it is not used at all. In some cases, it is more expensive to buy the packaging and pay a person to collect the produce than the price they will pay in the supply chain for the product. When prices are high, everything is harvested and that has a relationship with minimal waste.	Pricing policy plays an important role in food losses. Lack of transportation, storage and refrigeration infrastructure.	The causes are poor planning, inadequate application of inputs, poor agronomic practices, incorrect post-harvest handling. Issues associated with logistics, packaging, shipping, poor infrastructure (roads are in bad condition).	Often the losses are not the direct responsibility of the farmer, but the circumstances of both commercialization and transportation and the economic situation of the crop at the time of harvest, for example, this year due to the winter season there is a high risk of having problems with the transportation of the crop. There are constant problems that farmers have due to common factors that happen in developing countries, such as power outages or delays that can jeopardize the grains being stored.
SUSTAINABLE AGRICULTURAL PRACTICES							

How would you describe the status of sustainable agricultural practices in Colombia?	Progress has been made, but coordinated efforts are needed between the productive and environmental sectors to ensure that small producers have access to environmental education and culture and that they are provided with an opportunity to guarantee food security while restoring nature	There are sustainable practices such as seed guardian teams, organic agriculture, and practices for water, land, forest conservation, albeit under difficult conditions.	Colombia is moving towards the adoption of sustainable practices due to international commitments, among the projects that stand out are the climate and green taxonomy. Similarly, the country is seeking to standardize processes and identify what are sustainable practices and what are not, what are green practices and what are not.	A current problem is the high cost of agrochemical inputs, which is reflected in production costs. Additional efforts are needed to regulate the use of agrochemicals through new practices and technological packages to improve the country's productivity.	There has been a remarkable development at the union level, trying to manage and learn about intelligent agriculture applications (satellite images, drones), but there is much more to do.	Although in Colombia food is still produced as in the green revolution, it has been identified that markets have evolved, they have become more specialized and people want to eat a product that comes from an environmentally responsible and healthy activity. Unions have begun to understand this trend and have integrated some sustainable practices in food production. These practices are acquired faster when participating in international markets, so national markets are lagging behind.	Certain practices have changed, such as calendar applications and broad-spectrum applications to control any possible pathogen that may exist in the crop. Farmers are currently more focused on monitoring in order to determine the biological problems that may occur in the crop, and based on them, with the support of Fedearroz, generate specific recommendations adapted to the needs of the crop at any given time.
What are the obstacles faced by Colombia in the implementation of sustainable practices in the agricultural sector?	The lines of action to be implemented or reinforced are: regulation, environmental education, promoting an environmental culture. There is a challenge of access to emerging technologies and cultural acceptability Substitution of synthetic agents by the production sector Focus on small farmers (5 hectares or less) so that they have access to environmental education and culture, while providing them with a scenario of opportunity and guaranteeing food security while restoring nature.	Floods that generate problems of displacement, poverty and misery. Lack of government support with resources and budget to help small farmers Lack of understanding and political will to support processes in communities. Risk to life (natural, animal and human). The risk of mining that generates economic resources but destroys nature. The risk of fracking in areas where it would affect water and permanent crops	There are no stable and favorable conditions over time in terms of prices and climate for farmers to adopt sustainable practices Culture plays a role in the rejection of sustainable practices by farmers Farmers usually have a low level of education	The entire technical assistance system must be strengthened Technology is only one part of the process, the other part is education and raising people's awareness.	Colombia has a law on the national agricultural innovation system, but it lacks a lot of implementation because it is not clear how to generate technical assistance for small and medium-sized farmers. There is also a lack of strategies from the university to emphasize certain practices in certain regions. The issue of assistance, education, as well as support and incentives for farmers - especially small and medium farmers - is fundamental. The implementation of simple practices is needed, not only technological change, that generate a change in behavior, which also require investments for people with knowledge to go to the field to give talks and raise awareness among producers.	The main issues are technological, knowledge, and an adequate implementation of environmental regulations by the Regional Autonomous Corporations is needed. The more knowledge, supply of information and programs that can encourage this kind of production, the more difficulties that the country has today can be overcome.	Dependence on the decisions of marketers and consumers, since certain friendly and sustainable practices, require additional investments. There is no differential in terms of commercialization, so there is no economic motivation for a farmer who wants to carry out these practices. Those who incur in these practices have inefficiencies or costs that are a little higher, which are not compensated via commercialization. The rice market is not rewarding good green initiatives with a price differential, so it is difficult for this type of practices to be extended to larger areas.
DIGITAL AGRICULTURAL TECHNOLOGIES							
Are digital technologies a key aspect in the implementation of sustainable agricultural practices in Colombia?	Entities in the productive sector, mostly in the private sector, have demonstrated that the technification of agricultural practices and the investment in emerging technologies represent an opportunity of great	The application of technology in agricultural production processes is key and digital technology can help increase productivity	Digital technologies are tools that can lead to sustainable practices, but additional strategies must be sought to enable small farmers to adopt the technologies.	For technology to operate and function, it needs to be combined with training and knowledge transfer, as well as generating appropriate technology packages for each crop.	At the union level, there are unions that have managed to develop technologies because they have better capabilities, for example, in the rice sector, progress is being made with intelligent agriculture for climate and irrigation issues. However, in general there is a significant lag	Technologies are key, but there are many gaps to be overcome in order to use them in the country. Information technologies have advantages for communicating and transferring knowledge.	There are many models with algorithms or programs that make it possible to determine what the disease thresholds are, if there are environmental or climatic conditions for a pathogen to become a problem. This allows farmers to know what they are going to face and, above all, what they have to control in the field.

	importance for the agricultural sector				and technologies are a necessity.		
Is the country's digital infrastructure ready for such a transformation?	Colombia has made significant progress in infrastructure development with large investments and generating growth, but the digital infrastructure is not yet ready	Colombia is a backward country; there is still a lot of artisanal agricultural production and machinery is scarce.	In Colombia there is still no connectivity in the countryside	Connectivity is a retardant for the development of technologies with adequate training and knowledge transfer, but it is also used as an excuse because there are offline developments that could be implemented.	The issue of digital technologies is very important but in Colombia there are still insufficient applications or development, connectivity in rural parts of the country is still insufficient.	Colombia has an important technological gap, the country uses technologies that are more than two centuries old, not only in tools and machines, but also in knowledge.	The country's infrastructure has too many shortcomings. Rural areas in Colombia have connectivity problems, not only in terms of roads, but also in terms of availability of internet networks. This means that many of the equipment, tools and platforms that can provide information support so that farmers can make better decisions do not work in rural areas. Farmers have to go to urban centers in order to have internet connection and be able to consult weather forecasts, prices, disease or pest monitoring results.
What are the obstacles faced by Colombia in the implementation of digital technologies in the agricultural sector?	Scaling up emerging technologies from the private sector to small farmers There is a need to strengthen intra-institutional and inter-institutional articulation and synergy, as well as with international cooperants interested in natural resource governance Bridging the gap between the productive and environmental sectors	Inadequate land distribution, flat fertile land where there is no sowing, while there are many small farmers in sloping areas where mechanizing and technifying is very complex. It depends not only on the producer, but also on resources, capital, agronomic and credit conditions Displacement of people from the countryside to the cities because profitability levels do not allow good economic conditions. Free trade agreements that ruin Colombian producers. Control of the entire supply chain by multinationals (from land management to final consumer).	Not all farmers are at the same technological level to adopt new digital technologies Small farmers do not have the resources and cash flow to be able to acquire the technologies. Adoption of technologies requires knowledge transfer to the rural area. Culture also plays a role in farmers' rejection of digital technologies Farmers think first about money rather than social and environmental impact. Lack of connectivity in the country and of networks in rural areas	It is not only the lack of connectivity that does not allow to reach producers, but also the combination of the lack of capacity building and having the technology at hand. Technology should not be everything, but a mean through which it is possible to achieve better agricultural practices. It is necessary to identify the needs and segment them to be able to develop the appropriate technology. The segment of smaller producers with technology restrictions must be better understood.	Climate variability has become more pronounced in recent years, which makes it necessary for farmers to be accompanied by these technologies so as not to jeopardize the best time to harvest. The main limitation is connectivity. There is still much to be done between research and practice to make changes in the agricultural sector, adding the need for incentives and awareness to make technological changes.	In the rural sector, accessibility to technologies is quite limited, network coverage with internet access via cellphone can be one of the main barriers. Need to use clear and practical language for farmers, rather than technical language that they do not understand. Generation gap in the Colombian countryside, there is an aging rural class and it is known that it is easier for young people to become familiar with the use of technologies.	If the country's connectivity is not improved, both in terms of roads and Internet networks, it will be difficult for the agriculture sector to migrate towards digital agriculture There is no way for the data generated in the field to reach the servers for processing, and the results of the simulations and models do not reach the farmers efficiently and effectively. Financing is another constraint, to generate digital agriculture, implementation costs are high. It is important to generate research and transfer programs so that the different institutions involved in rice research have the technical and financial facilities to acquire technology and to show farmers the advantages of its applications and actively support them. Lack of mechanism or means to finance technology initiatives and to make them widespread.

Appendix 10: Assessment of the recommendations

Solution	*Recommendations*																			
	Economic benefits						Social (Knowledge and training)								Environment management					
	Crop Yield	Prices	Seed quality	Financial support	Investments	Production costs	Fertilize crops	Pest and disease control	Soil variability	Seed placement	Monitor nutritional status	Agricultural practices	Make difficult decisions under unclear situation	Weather forescasting	Water scarcity	Water in difficult access areas	Irrigation	Soil nutrition	Soil erosion
System of Rice Intensification (SRI)	x						x	x			x	x			x	x		x	x
Push and Pull system for pest control	x							x		x		x							x
Intercropping	x										x	x						x	x
Conservation tillage	x						x				x	x							x
Rice husks as fertilizer	x				x	x	x	x				x						x	
Solar-Powered Irrigation System	x											x			x	x	x		
Soil analysis system	x						x	x	x		x	x	x					x	x
Digital platform I		x	x	x									x						
Digital platform II			x	x	x								x	x					
Mobile application		x				x		x			x		x	x					