DISSERTATION

HUMAN SYSTEMS INTEGRATION OF AGRICULTURAL MACHINERY IN DEVELOPING ECONOMY COUNTRIES: SUDAN AS A CASE STUDY

Submitted by

Hamza Ahmed

Department of Systems Engineering

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2022

Doctoral Committee:

Advisor: Erika Miller

James Owiny
Steve Simske
Becca Jablonski
Daniel Herber

ABSTRACT

HUMAN SYSTEMS INTEGRATION OF AGRICULTURAL MACHINERY IN DEVELOPING ECONOMY COUNTRIES: SUDAN AS A CASE STUDY

Widespread adoption of agricultural machinery for developing economy countries is commonly regarded as a fundamental component of pro-poor growth and sustainable intensification. Mechanized farming can also improve perceptions of farming and mitigate rural-out migration. However, many traditional farmers do not have access to machinery and/or the machinery is cost prohibitive. This study applies the systems engineering approach to identify human-systems integration (HSI) solutions in agricultural practices to more effectively adapt technologies to satisfy traditional farmers' needs. A treatment control study was conducted on 36 farms in Sudan, Africa, over three farming seasons: 2019 (baseline), 2020, and 2021. The treatment group farmers (N = 6) were provided with agricultural machinery (i.e., tractor, cultivator, planter, and harvester), fuel for the machinery, and training to use the machinery. Farmers were interviewed at the beginning of the study, and then after each planting and harvesting season during the study.

Findings show that the most significant barriers for technology adoption were culture, security, and maintenance costs. However, they also reported that the most significant challenges in their nonmechanized farming practices were related to labor, safety, and profit margins, all of which could be addressed with machinery. Moreover, the results show that all farmers had similar net-profits in 2019, when farming without machinery, while mechanized farming yielded significantly higher net-profits ($16.61 per acre more in 2020 and $27.10 per acre more in 2021). Farmers also provided needs and rationales of various design options in tractors and attachments.

The findings of this dissertation suggest that, despite the initial resistance to using agricultural machinery, the farmers were pleased by their experience after using farming machinery and expressed an even more accepting attitude from their children towards this new farming process.

These results demonstrate the importance of developing effective solutions for integrating farming technology into rural farming practices in developing economy countries. More broadly, this study can be used as an HSI framework for identifying design needs and integrating technology into users' lifestyle. The results presented in this dissertation provide a quantified difference between farming with and without machinery, which can provide a financial basis for purchasing and borrowing models, machinery design requirements, and educational value to farmers. Further, the financial values and design requirements can help inform farmers regarding expected costs, returns, and payoffs from tractor adoption. Manufacturers and policy makers can utilize this to promote technology adoption more effectively to farmers in developing economy countries.

ACKNOWLEDGMENTS

To my advisor, *Dr. Erika Miller*, I would like to express my most sincere gratitude for all of the guidance, encouragement, patience, and opportunities you have provided me. I will always be grateful for the fantastic example you have been as a mentor.

To each member of my committee:

Dr. Steve Simske, thank you for all the knowledge that you give to me.

Dr. James Owiny, thank you for your great mentorship.

Dr. Daniel Herber, thank you for all the help and support.

Dr. Becca Jablonski, I deeply appreciate your effort in setting me up for success.

I appreciate all of your support throughout my graduate studies

To my family:

Fakiha, Thank you for the support

Khattab, Thank you for all the nice moments

Shahd, thank you for bringing the joy to my life

Thank you for all the love, faith, and laughs along this journey. This dissertation would not be possible without each and every one of you.

Thank you.

TABLE OF CONTENTS

ABSTRACT ii

ACKNOWLEDGMENTS iv

LIST OF TABLES ix

LIST OF FIGURES xii

INTRODUCTION 1

LITERATURE REVIEW 3

2.1 Human Systems Integration Overview 3

2.2 Importance of Agricultural Technology 4

2.3 Benefits of Agricultural Technology 5

2.4 Factors Influencing Adoption of Agricultural Technology 7

2.5 Agricultural Technology Design Considerations 9

2.6 Farming Technologies Used in Industrialized Countries 10

2.7 Common Farming Machinery 12

2.8 Equipment Used in Traditional Farming 18

2.9 Farm Sizes 20

2.10 Types of Farmers 21

2.11 Agriculture Machinery Adoption Initiatives 22

2.12 Summary of Importance of Agricultural Machinery 24

2.13 Economic and Financial Models 25

2.14 Rational for Implementation in Sudan 27

2.15 Disadvantages of using Modern Technology in Agriculture: 29
2.16 Gaps in Literature 31
METHODOLOGY 33
3.1 Participants 33
3.2 Farming Equipment 36
3.3 Interview Structure 36
3.4 Terms Definitions 38
3.5 Data Cleaning and Analysis Methods 38
AGRICULTURAL MACHINERY: PRECEPTION OF ADOPTION 40
4.1 Overview 40
4.2 Methods 40
4.3 Treatment Group Demographics 40
4.4 Traditional Farming Practices [Before Machinery] 42
4.5 Challenges with Traditional Farming [Before Machinery] 44
4.6 Willingness to Adopt New Technology 49
4.7 Synthesizing Perceived Benefits and Challenges 53
4.8 Machinery Impact: After Planting in 2020 53
4.9 Machinery Impact: After Harvesting in 2020 56
4.10 Machinery Impact: Before Beginning of Second Mechanized Farming Season [2021] 58
4.11 Machinery Impact: After Planting in 2021 63
4.12 Machinery Impact: After Harvesting in 2021 65
4.13 Chapter Summary and Discussion 75

ECONOMIC IMPACT OF AGRICULTURAL MACHINERY 78

5.1 OVERVIEW 78

5.2 METHODS 78

5.3 SIMILARITIES IN FARM CHARACTERISTICS 79

5.4 FACTORS AFFECTING FARMING NET-PROFITS 80

5.5 BREAKDOWN OF COSTS 83

5.6 COST OF FUEL TO FARM WITH MACHINERY 84

5.7 COST, REVENUES, AND NET-PROFITS BETWEEN GROUPS 85

5.8 NET-PROFIT BENEFIT OF MACHINERY 99

5.9 RETURN ON INVESTMENT (ROI) BETWEEN GROUPS 100

5.10 RETURN ON INVESTMENT (ROI) BENEFIT OF MACHINERY 104

5.11 CHAPTER DISCUSSION AND SUMMARY 105

5.12 CHAPTER CONCLUSIONS 108

NEEDS AND REQUIREMENTS ANALYSIS ON TRACTOR DESIGN 110

6.1 OVERVIEW 110

6.2 METHODS 110

6.3 FARM SIZES 111

6.4 OWNING OVER RENTING A TRACTOR 112

6.5 TRACTOR DESIGN PREFERENCES 113

6.6 DECIDING FACTORS TO USE TRACTOR MACHINERY 117

6.7 ACCESSORIES ON FARMING MACHINERY 119

6.8 DESIGN VALIDATION 120

6.8.1 MARKET COMPARISON 120

6.8.2 PAYOFF MODELS 121
6.9 CHAPTER DISCUSSION AND SUMMARY 123
6.10 CHAPTER CONCLUSIONS 125
GENERAL CONCLUSIONS & SUGGESTIONS 126
7.1 OVERALL FINDING 126
7.2 SUGGESTIONS 130
7.3 CONTRIBUTIONS 132
7.4 LIMITATIONS AND FUTURE RESEARCH 134
REFERENCES 137
APPENDIX: TRANSLATED INTERVIEW QUESTIONS 147

LIST OF TABLES

Table 1. Factors Influencing the Adoption of Agricultural Technologies 7

Table 2. Main Types of Tractors 12

Table 3. Soil Cultivation Machinery 13

Table 4. Seed Planting Machinery 15

Table 5. Fertilizing and Pest Control Machinery 16

Table 6. Harvesting Machinery 17

Table 7. Equipment Used in Traditional Farming 19

Table 8. Sudan's Economy by Economic Sector 28

Table 9. Demographics of Farms in the Study 34

Table 10. Structure of Interviews for Both Groups 37

Table 11. Farm Characteristics for Treatment Group 41

Table 12. Themes for Traditional Farming Practices 42

Table 13. Key Challenges in Traditional Farming 45

Table 14. Themes for Interest in New Technology 49

Table 15. Themes for Willingness to Adopt Technology Given the Opportunity 51

Table 16. Experience Using Machinery for Planting 54

Table 17. Experience Using Machinery for Harvesting 57

Table 18. Expectations before the beginning of the second farming season 59

Table 19.Experience Using Machinery for Harvesting 63

Table 20. Questions related to the harvesting operation 66

Table 21. Questions related to the experience of using machinery 67

Table 22. Farmers Willingness to Adopt Farming Machinery 68

Table 23. farming machinery impacts 72
Table 24. Exchange Rates for Black-Market and Official Markets Between USD and SDG..... 82
Table 25. Summary of Farming Costs ($/acre) by Category and Machinery Group..... 83
Table 26. Fuel Costs for Entire 2021 Farming Season 84
Table 27. Summary of Financial Data ($/acre) for Control Group..... 85
Table 28. Control Group 2019 Farming Season Costs 86
Table 29. Control Group 2019 Farming Season Revenue 87
Table 30. Control Group 2019 Farming Season Net-Profits 88
Table 31. Control Group 2020 Farming Season Costs 89
Table 32. Control Group 2020 Farming Season Revenue 90
Table 33. Control Group 2020 Farming Season Net-Profit..... 91
Table 34. Control Group 2021 Farming Season Costs 92
Table 35. Control Group 2021 Farming Season Revenue 93
Table 36. Control Group 2021 Farming Season Net-Profits 94
Table 37. Summary of Financial Data ($/acre) for Treatment Group 95
Table 38. Treatment Group 2019 Farming Season Costs..... 95
Table 39. Treatment Group 2019 Farming Season Revenue..... 96
Table 40. Treatment Group 2019 Farming Season Net-Profits 96
Table 41. Treatment Group 2020 Farming Season Costs..... 96
Table 42. Treatment Group 2020 Farming Season Revenue..... 97
Table 43. Treatment Group 2020 Farming Season Net-Profits 97
Table 44. Treatment Group 2021 Farming Season Costs..... 97
Table 45. Treatment Group 2021 Farming Season Revenue..... 98

Table 46. Treatment Group 2021 Farming Season Net-Profits 98

Table 47. ROI Data for Each Control Group Farmer by Year..... 101

Table 48. ROI Data for Each Treatment Group Farmer by Year 102

Table 49. Summary of ROI by Machinery Group 104

Table 50. Descriptive Statistics of Farm Sizes 111

Table 51. Tractor Feature Preferences 115

Table 52. Comparing Farmer's Needs to Tractor Available in Market..... 121

Table 53. Payback Model for Entire Δ Net-Profit 122

Table 54. Payback Model for Percentage of Total Profit 123

LIST OF FIGURES

Figure 1. Agricultural GDP as a percentage of total GDP 28

Figure 2. Agricultural labor as a percentage of total labor force 29

Figure 3. Reported problems with current farming practices 45

Figure 4. Benefits and barriers to technology adoption 53

Figure 5. Likely of using farming machinery 71

Figure 6. Machinery helpfulness in land preparation 73

Figure 7. How easy was using farming machinery 73

Figure 8. Machinery use in planting operations 74

Figure 9. Using machinery in harvesting 74

Figure 10. Factors that affect farming net-profits as identified by farmers 81

Figure 11. Net-profit per acre in USD based on exchange rates, mean +/- SD 82

Figure 12. Comparison of net-profit ($/acre) with and without farming machinery, mean 99

Figure 13. ROI comparison for control group farmers over the 2019, 2020, and 2021 102

Figure 14. ROI comparison for treatment group farmers over the 2019, 2020, and 2021 103

Figure 15. Comparison of ROI with and without farming machinery, mean +/- SD 105

Figure 16. Reasons for owning farming machinery 112

Figure 17. Tractor Design Preferences 114

Figure 18. Deciding factors to use Tractor machinery 118

Figure 19. Reasons For not to Have Accessories on Farming Machinery 119

Chapter 1

INTRODUCTION

Human-Systems Integration (HSI) is a crucial factor for technology adoption, as it focuses on studying the human factors behind a possible technology adoption. In the case of this dissertation, HSI is applied to agricultural machinery adoption by traditional farmers in Sudan, Africa. Boy and Narkevicius (2014) explained that a human-centered approach applied to systems engineering leads to appropriate HSI and more successful systems. Hence, this study aims to utilize a human systems integration approach for improving technology adoption in rural traditional farming practices. Previous literature suggests that increasing production, such as through increased use of farming machinery, can have a significant impact on reducing poverty in developing economy countries. However, there is limited research quantifying the differences in mechanized farming for these rural farmers and focusing machinery design and integration from the user's perspective.

This study's overall objective is to utilize a systems engineering approach to identify human-systems integration opportunities in agricultural practices in Sudan, Africa, which could more broadly be applied to any developing economy country. The specific research aims are:

- *Research Aim 1: Evaluation of current farming practices.* What are the current farming practices used by traditional farmers in Sudan, and why?

- *Research Aim 2: Impact of farming machinery.* What are the initial perceptions of technology? What are the barriers to adoption? How does machinery impact lifestyle? How does machinery impact crop production?

- *Research Aim 3: Requirements of farming machinery.* What do farmers need in their equipment? How much would farmers be willing to spend to use/own equipment? What machinery would be the optimal solution?

Ultimately, this research aims to identify traditional farmers' concerns regarding agricultural machinery adoption and then develop a more adaptive solution to achieve long-term, sustainable use by the farmers.

Chapter 2

LITERATURE REVIEW

This chapter summarizes the current state of knowledge regarding agriculture machinery adoption by traditional farmers and the use of farming machinery in farming processes. Previous research and reports have discussed agriculture in developing economy countries and how vital agriculture is for the people in these countries, since most of the human labor in such countries is used in the agriculture sector. However, previous literature does not adequately address the relationship between humans and machinery in the agriculture field; and, more specifically, how to enhance the trust (i.e., acceptance and adoption) between humans and machinery. This is important for the agricultural sector to become more efficient and more rewarding for farmers and for the overall economy of the developing countries. This chapter aims to highlight the importance of integrating humans with machinery in developing economy country's agriculture field and the potential impact on improving the farming process with mechanized farming.

2.1 Human Systems Integration Overview

Human-Systems Integration (HSI) is the area of systems engineering that focuses on a system's human components and elements to help resolve system designs that do not adequately consider the human aspect. HSI is the interdisciplinary technical and management processes for integrating human considerations within and across all system elements, an essential enabler to systems engineering practice (Ahram et al., 2009). It provides a model for explaining human performance as a function of human factors engineering domains, such as through personnel, training, workforce, environment safety and occupational health, habitability, and survivability.

Human-Systems Integration is crucial for technology adoption. A human-centered approach applied to systems engineering leads to appropriate HSI and more successful systems (Boy & Narkevicius, 2014). For example, in developing economy countries, particularly in relation to the adoption of agricultural technology, it is important to consider the users' education, poverty, and culture (Higgins, Bryant, Howell, & Battersby, 2017; Pamuk, Bulte, & Adekunle, 2014).

However, many of the previous studies that look at the adoption of farming technology in developing economy countries lack the perspective of a HSI approach. In many of the previous efforts, the focus has been technology-centric, rather than considering the users' needs and preferences and the impact of adoption on the local community. For example, previous literature has focused on the technical feasibility of machine integration rather than cultural influences on adoption (Bechar & Vigneault, 2016; Charlton, Taylor, Vougioukas, & Rutledge, 2019). Oftentimes, the perceived benefits of fully adopted farming technology (e.g., reduced poverty, improved quality of life, and food production) overlook the barriers and challenges from the farmer's perspective during the implementation period.

2.2 Importance of Agricultural Technology

In the agricultural industry, farming machinery and technology have existed for a long time, but limited information is available to traditional farmers on the factors influencing the adoption of this farming technology (Wilkins, 2008; Yusuf & Malomo, 2007). Mechanized farming has long been regarded as fundamental in poverty reduction for developing economy countries. This is largely because adoption of agricultural technologies targets acceleration for farmers below the poverty line, addressing pro-poor growth. In general, agricultural machinery has been associated with improving soil cultivation, water supply, crop index, reducing loss, and overall improved resource efficiency (Sugiardi, 2021).The use of farming machinery has become

crucial in all farming processes, ranging from pre-planting, planting, harvesting, post-harvesting, to distributing goods to market (Martin-Clouaire & Duru, 2013; Sugiardi, 2021).

2.3 Benefits of Agricultural Technology

Previous literature suggests that the adoption of agricultural technology in developing economy countries offers numerous benefits on both an individual and societal level. Farming technology can improve the well-being and quality of life for traditional farmers (Doss, 2001). This is largely due to the fact that these technologies can enhance agricultural production quality and quantity, and in return, reduce poverty among farmers (Alene & Coulibaly, 2009; Muzari, Gatsi, & Muvhunzi, 2012). Farming technology (e.g., tractors, irrigation systems) can produce economic transformation for developing economy countries through sustained agricultural growth (Sheahan & Barrett, 2017). (Pamuk et al., 2014) considers agricultural innovations, such as farming technology, as a pre-condition for sustainable pro-poor growth, which refers to stimulating economic growth specifically among low-income individuals. In addition to increasing income and lowering poverty for farmers, technology offers improved nutrition, lower food prices for staple foods, and even employment opportunities for non-farmers (Kasirye, 2013; Mwangi & Kariuki, 2015). Farming technology can also make farmers more resilient to climate and weather (Callo-Concha, 2018) and improve farmers' adaptability to weather extremes (Boansi et al., 2017a).

The use of farming machinery can accelerate and improve the quality of water supply, soil cultivation, planting intensity, livestock productivity, increase overall productivity and resource efficiency, and reduce lost yields (Gonzales, 1993; Hutahaean, Anasiru, & Sarasutha, 2005). Tractors specifically increase production efficiency by decreasing time and effort spent on cultivation, sowing, spraying, crop establishment, harvesting, and post-harvesting operations

(Kienzle, Ashburner, & Sims, 2013a). Moreover, the use of farming machinery results in efficient use of human resources, costs, and time of harvest (Sugiardi, 2021). This is particularly important, as labor scarcity in agriculture continues to increase, the use of farming machinery can help increase the smallholder farmers' total production efficiency and returns to costs while alleviating the constraints of labor (Biggs, Justice, & Lewis, 2011; Khondoker Abdul Mottaleb, Krupnik, & Erenstein, 2016).

A significant benefit of mechanization is the improvements it provides in the efficiency of agricultural labor (Friedrich, 2013), and in turn, minimizing rural out-migration. Farming with little to no machinery induces high labor drudgery (Baudron et al., 2015) and the addition of mechanization can significantly reduce this drudgery (Kienzle et al., 2013a). The physically demanding labor caused by low mechanized farming has made farming unattractive to youth, disproportionately affects women, and is often regarded as a "dirty job" (Baudron et al., 2015; Gartaula, Niehof, & Visser, 2012). These changes in perception of farming for a living, particularly in the reluctance of younger generations to farm, has led to rural out-migration (Gartaula et al., 2012). Specifically, where younger generations are moving out of rural areas towards cities. Rural out-migration has further exasperated increasing labor scarcity, leading to increasing labor costs, which is particularly challenging for cash-constrained smallholder farmers (Gregg, Colton, Matin, & Krupnik, 2020). Not only does this influence labor costs, but also threatens food security for these countries (Gartaula et al., 2012). Hence, it is believed that farming machinery can help incentivize younger generations to remain involved in agriculture and rural communities ((USAID), 2016).

Economically, the utilization of farming machinery affects the well-being and quality of life for traditional farmers. Agricultural production and productivity depend largely on many

factors such as the quality of land, availability of farming inputs, and the economic stability in the farming area (Yadav et al., 2013). Achieving the balance between productive agricultural enterprise and efficient environmental protection sustainability is essential to making the agriculture sector economically viable (Yadav et al., 2013). It is believed that using farming machinery can improve the farmer's livelihoods since farming machinery helps increase agricultural productivity and eventually improves the millions of poor farm households by adding more annual income to each farming family (Doss, 2001). Farming machinery can improve the financial situation for the rural communities by incentivizing young people to remain involved in agriculture since rural out-migration is particularly popular among young people, who appear to be less interested in engaging in farming as a livelihood pursuit.

2.4 Factors Influencing Adoption of Agricultural Technology

Tey & Brindal (2012) define seven categories and associated factors to explain farmers' ability to adopt agricultural technology. These factors are provided in Table 1. These factors include individual farmer, farm characteristics, and technology attribute level considerations.

Table 1. Factors Influencing the Adoption of Agricultural Technologies (Tey & Brindal, 2012)

Categories	Factors	
Socio-Economic	• Operator age • Years of farming experience • Formal education	
Agro-Ecological	• Land tenure • Farm specialization • Farm size	• Part-owner farmers • Full-owner farmers • Farm income/profitability

	• Farm sales • Variable fertilizer rates • Livestock sales • Debt-to-asset ratio • Production value • Owned land minus rented land • Yield	• Soil quality • Percentage of the main crop in total farmland • Percentage of farmland as county land area • Percentage of cropped land to total farmland • Percentage of farmland as large farms • Off-farm employment
Institutional	• Distance from a fertilizer dealer • Region	• Use of forwarding contract • Development pressure
Informational	• Use consultant • Perceived usefulness of extension services in implementing precision farming practices	
Farmer Perception	• Perceived profitability of using precision agriculture	
Behavioral	• Willingness to adopt variable-rate technology	
Technological	• Yield mapping • Use of computer • Farm has an irrigation facility • Generated own map-based input prescription	

2.5 Agricultural Technology Design Considerations

Agricultural technology, just like other consumer products, should address the needs of their users. However, it can be challenging to address all client requirements, especially as the agricultural sectors competitive demands have led to increased complexity of customer needs (Marini & Romano, 2009). Farm mechanization is a viable solution for developing economy countries to improve their rural economies and address labor shortages (Xiong et al., 2018). Hence, manufacturers need to understand the specific needs of these farmers and their farming operational characteristics (Marini & Romano, 2009), and integrate these needs into machinery design (Yao et al., 2016; Wang & Zhang, 2019).

Previous and recent efforts in farm mechanization have focused on tractor designs to increase engine power, capacity, attachments, reliability, and decrease operating expenses and labor (Yadav et al., 2010). Xia et al. (2020) used parameter optimization to improve tractor power transmission design, which they considered a critical component in meeting design requirements for tractor operational environments. Gorjian et al. (2021) explored farming machinery designs that integrated solar power, to achieve more sustainable farming operations. Some studies have also included some user characteristics in their tractor designs. For example, Yadav et al. (2010) measured the strength of 105 agricultural workers to design their machineries hand and foot controls. Similarly, Vyavahare and Kallurkar (2012) performed a meta-analysis on studies that used anthropometric and strength data to design agricultural equipment and reported that these design parameters can improve machinery safety, efficiency, and comfort. These previous works have focused on machinery design to improve operations and decrease costs, which is an important consideration to enhancing the farming inputs to outputs ratio. However, these efforts are also too

focused on costs and crop intensity and may have detrimental effects on small farms in developing economy countries (Banerjee & Punekar, 2020).

2.6 Farming Technologies Used in Industrialized Countries

Many developed countries have limited agricultural resources, but using agricultural technology systems allow these countries to maximize their limited resources (Mougeot, 2000). Agricultural technology in developed countries can be classified into four main categories: mechanical technology, biotechnology, chemical technology, and infrastructure technology. The focus of this dissertation is on mechanical technology.

2.6.1 Mechanical Technology

Mechanical agricultural technology was introduced to replace human and/or animal labor. Mechanical agricultural technology is a labor-saving and capital-intensive type of technology (Duffy, 2009). There is a history of the development of agricultural mechanical technology methods and their role in saving costs, increasing production, and reducing the time required to conduct agricultural operations. Mechanized agricultural technology methods include soil preparation, seeding, lining, skewing machines, fertilizer spreaders, pesticide spraying machines, harvesting and threshing machines, and irrigation machines (Schmitz & Moss, 2015).

2.6.2 Biotechnology

One of the leading agricultural technologies in the modern world is biotechnology. This type of technology is represented in developing new varieties and strains in the plants and animal fields (Herdt, 2006). It is characterized by high productivity and resistance to diseases and pests by using genetic engineering and implants developed in plant tissue or using biological resistance as an alternative to chemical pesticides that are harmful to the environment, humans, and animals when it exceeds a certain limit (Wieczorek, 2003). One method of agricultural biotechnology is

the use of living organisms in the production or modification of farm products or the development of new microorganisms for specific uses. Biotechnology methods include developing improved strains for different crops and improving animal breeds to raise their production efficiency in meat, milk, and eggs (Herdt, 2006). Agricultural biotechnology is considered a type of technology that encourages farmers to continue farming because it increases yield per land unit, which means more income to farmers (Wieczorek, 2003).

2.6.3 Chemical Technology

Chemical technology includes technologies that use the energy resulting from interactions between chemical elements. Chemical technology includes chemical pesticides, growth regulators, and agricultural fertilizers (Davydov, Sokolov, Hogland, Glinushkin, & Markaryan, 2018). The use of chemical technology methods aims to address any deficiencies in the farming lands and compensate for any deficiency in the land. Chemical technology methods are also necessary to combat diseases and pests that harm the crops (Vasilevski, 2003).

2.6.4 Infrastructure Technology

In modern agricultural systems, infrastructure technology is represented in using the modern mechanisms related to irrigation and drainage equipment and preserving soil fertility through improving lands by deep plowing under the soil, cleaning canals and drains (Heerink, 2005; Rao, Birthal, & Joshi, 2006; Totin et al., 2014; Vanlauwe et al., 2010). Infrastructure technology is also associated with all marketing and transactions in the post-harvest phase, whether in relation to storing agricultural products, transportation, manufacturing, and processing the agricultural products for export and agricultural information infrastructure (Bationo & Waswa, 2011; Johnston & Mellor, 1961).

2.7 Common Farming Machinery

Since ancient times and all over the world, many types of farming machinery have been used in farming to help farmers grow and harvest their crops. Farmers generally need some sort of farming machinery to process and prepare the land and soil, fertilize and harvest the crops, and for transportation. Some of these machines are developed to be used for specific types of farming operations and in particular areas in the world, since not all areas are the same, such as differences in weather, climate, crop type, soil type, land type, and, most importantly, the farmer's needs.

The most common and most crucial farming machinery is the tractor, see Table 2. The tractor does not work by itself; it must be connected or mounted with other implements to perform the farming process. The tractor also provides the needed power to operate the machines that are drawn behind it. In some farming practices, farmers use tractors to operate other farming equipment such as feed grinders, pumps, and electric power generators.

Table 2. Main Types of Tractors

Tractor	Description	Example	Reference
Two-Wheel Tractor	Used mainly in small scale farms.		New Holland Tractor Company
Tracked Tractor (Four Wheel)	Used in all types of farms and is the most common.		John Deere Tractor Company

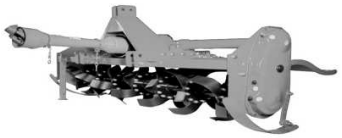
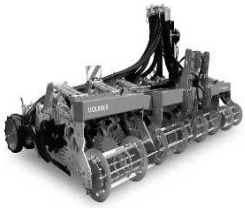
The other farm machinery, which are generally used in conjunction with a tractor, can be classified into four different types based on their use: (1) soil cultivation; (2) planting seed, (3) fertilizing and pest control, (4) harvesting.

2.7.1 Farm Machinery Used for Soil Cultivation

Soil cultivation is a process of pulverizing and stirring the soil before planting. It is necessary for removing weeds and to aerate and loosen the soil after the crop has begun to grow (van der Lely, 1985). The common tools used in soil cultivation are provided in Table 3.

Table 3. Soil Cultivation Machinery

Machinery	Description	Example	Reference
Cultipacker	Used to eliminate air pockets, crushes dirt clods, and presses down small stones to create a smooth, firm seedbed		Micro Food Company
Cultivator	Used to pulverize and stir the soil before planting or removing weeds and aerating and loosening the soil after growing		Northern Tool Company
Harrows	Used for soil surface cultivation. The harrowing primary use is to break up the soil lumps and provide a more refined finish, a		Land Pride Company

	good soil structure that will be ideal for seeding and planting.		
Plough/Plow	Used for the initial soil cultivation: bring to the surface fresh nutrients by turning over the soil's upper layer. This increases the retention of moisture and aerates the soil.		Universal Tool Company
Rotary Tiller	A motorized grower that uses spinning blades to turn over the soil's upper layer.		Titan Company
Strip-Till	Used to disrupt only the portion of the soil comprising the seed line. Combines the soil drying and heating advantages of traditional tillage with the no-till soil.		VOLMER Company

2.7.2 Farming Machinery Used for Planting Seed

Farmers can use machinery to assist in placing the seeds into the soil, which can increase speed and more efficient use of the land space, see Table 4.

Table 4. Seed Planting Machinery

Machinery	Description	Example	Reference
Broadcast Seeder	Known as a fertilizer or spreader. It is a commonly used crop, lime, or fertilizer spreading tractor tool.		Northern Tool Company
Seed Cum Fertilizer Drill	Used to drop and spread fertilizer evenly on the field. This machine has two boxes, one for fertilizers and one for seeds.		Plant Fertilizer Company
Seed Drill	Used for placing the seeds at a controlled depth and at a uniform rate, then covering the seed with the soil. This ensures that the seed distribution is at the exact seeding depth and rate.		Northern Tool Company

2.7.3 Farming Machinery Used for Fertilizing and Pest Control

There are many types of machines that can be used in fertilizing and pest control, three examples are provided in Table 5.

Table 5. Fertilizing and Pest Control Machinery

Machinery	Description	Example	Reference
Manure-Spreader	Known as a honey wagon or muck spreader. Used for fertilizing and spreading the manure over a field.		Meyer Company
Slurry Tank	Machine with a pump and tank that can fertilize the fields with slurry (a combination of water and manure).		Massey Ferguson MF
Sprayer	Used to apply pesticides, fertilizers, and herbicides to farm crops.		John Deere

2.7.4 Farming Machinery Used for Harvesting

Harvesting is arguably the most important phase of the cultivation process, and it is the process of gathering a ripened crop. In the past, harvesting was done manually, and due to that, a substantial portion of the crop was wasted. However, after introducing harvesting machines, harvesting has become more accessible and cheaper than ever. Harvesting machines have also saved time and reduced the quantity of waste to a great extent, see Table 6.

Table 6. Harvesting Machinery

Machinery	Description
Crop Harvesting	Harvests forage crops cultivated in upland/paddy fields and forms roll bale simultaneously.
Grain Harvesting	Used to harvest fruit seeds of a cereal crop, the edible brans, and grains.
Root Crop Harvesting	Used to harvest rooted crops.
Threshers	Used for the separation of grain from stalks and husks.
Vegetable Harvesting	Used to harvest different types of vegetables.

2.8 Equipment Used in Traditional Farming

Farming has been practiced by humans since the dawn of time. As such, farming equipment has a long history of improvements and modifications. Stone and wood were used to make the first farming tools (Ocampo, 2014). Among them were the stone adz, a sickle or reaping knife with sharpened stone blades used to gather grains, the digging stick, which was used for planting seeds and later as a spade or hoe, and a rudimentary plow, a modified tree branch used to scratch the soil surface and prepare it for planting. The plow was later modified so that it could be pulled by oxen. Tool and implement improvements have had significant impacts on the farming process. For example, the shift to using metal for tools made them more durable and efficient as compared to stone and wood (Ocampo, 2014).

There are three primary stages of the farming process that traditional farmers need tools for: (1) planting: the process where farmers put the seeds in the soil; (2) fertilizing: the process of adding fertilizer to the soil; and (3) harvesting: when the farmers gather the matured crops (Hassan, 2015). Traditional agricultural equipment is often made by hand and requires human labor to move. Conversely, modern agricultural equipment employs machines to perform the work. Further, the equipment used by traditional farmers require little to no maintenance (Belal, Abdallah, Qishuo, Abaker, & Talha, 2015). Even though there are differences between modern and traditional agricultural equipment, some farmers prefer to use traditional agricultural equipment. This could be due to their familiarity with the equipment, where the work may appear difficult to others, but for them, it is routine because they do it every day (Yale, 2015). The list of farming equipment's used in traditional farming are in Table 7.

Table 7. Equipment Used in Traditional Farming (Yale, 2015)

Tool	Description
Cleaner	Used for cleaning dirt on the plant.
Cutting Equipment	Used to cut harvest.
Hoe	Used for cleaning grass, digging, and leveling the land. It's usually made of wood or iron.
Machete	Made of iron and used to cut obstacles or logs that are larger in size.
Plow	Used in leveling the soil after plowing.
Plug-in	Used in planting seeds so that it is easier than using no tools at all.
Pry Equipment	Used for digging the soil and weeds the grass in the fields.
Rake	Used for throwing straws, lifting, and throwing leaves. Generally made of wood and has a long handle and a fork-shaped tip.
Rice Humping Equipment	Used to shed rice from its stalks during the harvest.
Ruler	Made of wood to line the land in the fields.
Sickle	A sharp and curved tool that is used for cutting grass around agricultural land.
Spray Equipment	Used to eradicate pests or organisms. It works as a container for spraying work to control pesticides.
Thresher	Used to remove seeds from the stalk by swinging plants on the tool. This tool is made of wood or bamboo.
Tillage Equipment	Used to plow a farming land to become loose and easy to plant seeds.
Weeder	Used to eradicate grass. It is made of wood with nails at the bottom.
Wood Planer Blade	A small knife that is used in the harvest.

2.9 Farm Sizes

Agricultural farms or lands are the sum of farmed land or cropland, including permanent [tree] crops and pasture area (Samberg, Gerber, Ramankutty, Herrero, & West, 2016). Farms can be classified into three different categories: small, medium, and large sized farms.

Small sized farms are defined depending on where they are located, as countries have different relative land sizes that would control the definition of farm size. For example, in China small size farms are any farm with less than 6.7 hectares (Wang et al., 2017), where a hectare (ha) is a unit of area and 1 hectare equals 2.47 acres. In Africa, small size farms are generally farms with less than 5 hectares (Muyanga & Jayne, 2019).

Medium sized farms are also defined based on the farm locations. For example, in China, medium sized farms are any farm that has a size between 6.7 to 20 hectares (Wang et al., 2017). In Africa, medium size farms are any farm that has between 5 to 20 hectares (Muyanga & Jayne, 2019). Farmers within this category, particularly in developing economy countries, predominately practice traditional farming techniques. In the case of this dissertation, most of the farmers included in this study have medium sized farms.

Generally, large farms have more than 20 hectares of land (Muyanga & Jayne, 2019; Wang et al., 2017). Many farmers within this category use farming technology and machinery in their farming process. Large size farms can be family owned or government/company owned.

2.10 Types of Farmers

There are many different types of farmers, which are generally defined by their farm size, annual agricultural income, use of farming machinery, and the way they perform the farming process (Stringer et al., 2020). Four of the primary farmer types can be defined within the scope of this dissertation: traditional smallholder farmers, traditional extensive farmers, semi-traditional large-scale commercial farmers, and modern farmers.

Traditional Smallholder Farmers. There are an estimated 570 million farms around the world, with roughly 85 percent (480 million) consisting of two hectares or less (Lowder, Skoet, & Raney, 2016). These farmers practice traditional farming with no use of any farming technology or machinery (Harris, 2019). Farmers of this category range from those who cultivate for subsistence to those who produce a modest surplus for the market. The income provided by traditional smallholder farms is rarely sufficient to ensure a decent living (Harris & Orr, 2014). Even with good traditional agricultural practices, these farms are frequently not financially sustainable, forcing land users to rely on other sources of income (Harris, 2019).

Traditional Extensive Farmers. Traditional extensive farmers typically have medium-sized farms of 20 to 50 ha, which they use to raise animals and various crops to increase their income by producing market-needed agricultural products (Rousseau, Gautier, & Wardell, 2015). These farmers are mainly traditional farmers who do not utilize any farming technology and exclusively use traditional farming techniques (Frey, 2007).

Semi-Traditional Large-Scale Commercial Farmers. These farmers typically use traditional farming methods on a vast scale and use farming technology in part of their process. These farmers have average farm sizes and are more common in countries with greater average per capita GDP (Lowder et al., 2016). Such traditional large-scale farmers are typically

commercially oriented, influenced by the markets they can access to maintain and increase their profitability in particular circumstances. They can work under a small company or in schemes controlled by the local governments (Borras Jr, Hall, Scoones, White, & Wolford, 2011).

Modern Farmers. These farmers use farming technology and farming machinery in their farming practices and they rely heavily upon all types of farming technology, such as insecticides and herbicides and farming machinery (Morton, Hobbs, & Arbuckle, 2013).

2.11 Agriculture Machinery Adoption Initiatives

There have been several studies and initiatives that have focused on the importance of using farming machinery in developing economy countries. (Biggs et al., 2011) studied mechanization in agricultural and rural development in Bangladesh, India, and Nepal. Similarly, (Khondoker A Mottaleb, Rahut, Ali, Gérard, & Erenstein, 2017) studied the effects in Bangladesh. (Kienzle et al., 2013a) compiled reports of efforts across Africa, Asia, South America, and Eastern Europe. (Berhe, 2016) focused on Ethiopia and (Baudron et al., 2015) reported across Eastern and Southern Africa. However, despite these identified benefits and needs, adoption rates of agricultural technologies remain low in developing economy countries (Mwangi & Kariuki, 2015). (Baudron et al., 2015) emphasizes the need for sustainable intensification (i.e., increasing land output without impacting the environment) to achieve food security in Africa, which requires improvements in farmers' access to machinery.

Small to medium sized farms are considered the foundation for food security in developing countries in sub-Saharan Africa and in South Asia (Gregg et al., 2020). However, there is a significant need to improve efficiency and productivity in their farming practices, especially through encouraging use of agricultural machinery, which has been a subject of scholarly debate for several decades (Kienzle, Ashburner, & Sims, 2013b). In particular, rural communities in

developing sub-Saharan Africa and South Asia are increasingly facing rural out-migration as some farmers leave their areas in search of more remunerative employment, which further exasperates the need for increasing efficiency and productivity of the farms (Gregg et al., 2020; Zhang, Rashid, Ahmad, & Ahmed, 2014). These labor scarcity challenges and reduced interest in farming has fueled the recent focus of agricultural machinery adoption policy and research (Mrema, Soni, & Rolle, 2014). As a result, Contemporary Development Initiatives have been introduced in developing countries to focus on introducing farm machinery, emphasizing the need for scale-appropriate mechanization and affordable equipment custom-designed for resource constrained small famers (Krupnik et al., 2013) These initiatives have also aimed to popularize rural entrepreneurial approaches by expanding smallholder farmers' access to agricultural machinery and technology (Gregg et al., 2020). Additionally, use of service provision arrangements have become increasingly popularly, where farmers can use machinery for an affordable fee from machinery owners (Khondoker Abdul Mottaleb et al., 2016). These machinery service provision arrangements alleviate the capital constraints that often hinders smallholder farmers access to machinery, while also providing income to machinery owners who can lend out their machinery after tending to their own fields (Keil, D'Souza, & McDonald, 2016).

As described above, despite these efforts, machinery adoption rates remain low. Hence, this research aims to capture perspectives of the farmers who are the intended targets of these initiatives and understand how to alleviate the gaps in knowledge and application. Further, this dissertation seeks to provide design requirements and cost models that can help inform about the impact and needs of farming machinery.

2.12 Summary of Importance of Agricultural Machinery

As discussed above, there are numerous studies that have shown the potential of machinery adoption in developing economy countries to improve their agricultural sectors viability. However, adoption remains low and traditional [manual] farming techniques are still largely deployed. The benefits of using machinery for these small to medium sized farms, as discussed previously, can be summarized as follow:

1. *Increase Farm Process Efficiency.* Increase speed and precision of operations, harvest, post-harvest, and crop establishment (Biggs et al., 2011; Kienzle et al., 2013b).
2. *Increase Production Efficiency.* Increase total production quantity and reduce costs while also alleviating the constraints of labor (Biggs et al., 2011; Khondoker Abdul Mottaleb et al., 2016).
3. *Increase Cultivated Areas.* Increase the amount of area farmers can manage by increasing efficiency of efforts.
4. *Improve the Farmer's Livelihoods.* Increased agricultural productivity eventually improves the millions of poor farm households' livelihoods by adding more annual income to each farming family (Doss, 2001).
5. *Improve Land Management.* More consistency in farming effort and alleviated workload on farmers from the machinery can help farmers more accurately plan for their farming processes.
6. *Diversify Crops.* Increased efficiency also means an opportunity to focus on other and/or more crops, and meet demand, which can reduce food insecurity.

7. *Reduce Farmer Drudgery.* Traditional farming requires a lot of manual labor, and it is increasingly hard to find enough laborers; using machinery can reduce farmers' drudgery, especially among children and women (Khondoker A Mottaleb et al., 2017).
8. *Reduce Rural Out-Migration.* Rural out-migration is particularly popular among young people, who appear to be progressively less interested in engaging in farming as a livelihood pursuit; machinery can incentivize young people to remain involved and active in agriculture and in rural communities by making farming less exhaustive and more technological advanced (USAID, 2016).

2.13 Economic and Financial Models

There are some financial models that are used to determine the financial feasibility of any investment or financial decision. Some of these financial models are:

*Return on Investment (ROI)***:** is the performance used to assess an investment's effectiveness or to compare the effectiveness of several distinct investments. ROI is calculated by dividing the Net-profit (return) by the investment's cost. The result is reported as a percentage or a ratio (Botchkarev, Andru, & Chiong, 2011). In other word ROI analyze the aims to achieve clarity in the decision-making process (Erdogmus, Favaro, & Strigel, 2004). The equation to measure the ROI is (Botchkarev et al., 2011);

$$\text{ROI} = \frac{\text{Net profit}}{\text{Cost}} * 100\% \quad (1)$$

The Net-profit is defined as the difference between cost and revenue (Al Hayek, 2018). The higher ROI, the better the investment is considered, and as long as ROI is positive, the net-profit is positive. For example, an ROI of 100% would indicate the revenue was double the cost (i.e., net-profit equaled cost), and an ROI of 0% would indicate the revenue equaled the cost (i.e., net-profit

of $0). ROI is used to improve traditional farmers' life, save, or make money, and increase farming productivity (Marcus, 2005).

Total Cost of Ownership (TCO): there are many definitions for the TCO depending on the where we apply it. TCO is a projection of the costs related to the acquisition, deployment, use, and disposal of a good or piece of equipment. TCO, measures the price of a purchase over the course of a product's whole existence (Ferrin & Plank, 2002; Marcus, 2005). Another definition for TCO is that the Total cost of ownership is defined as a philosophy for understanding all relevant supply chain-related costs of doing business with a particular supplier for a particular good/service. Also, The total cost of ownership (TCO) considers the total cost of acquisition, use/administration, maintenance, and disposal of a given item/service (Ellram, 2002). In summary, the (TCO) Total Cost of Ownership is used in case there is more than one option, and we want to determine the best option in term of the financial cost over the factor of time.

Local Economic Assessment (LEA): it's used to describe the economic opportunities, issues, and challenges in a specific area or the entire country. LEA is often used to understand the nature and extent of the problem. Specifically, it is used to better understand how the market, community, or the environment is affected by an issue and what supporting evidence is available to justify action (Bauer & Craig, 2008).

In my dissertation, I will use the ROI as a financial method to evaluate the economic benefits of using or adopting farming machinery by traditional farmers and evaluate the value and efficiency of machinery, as the ROI uses the net-profit and cost as financial factors what make it the most relevant financial model to this study.

2.14 Rational for Implementation in Sudan

Sudan Africa was selected as the case study for this research. Sudan has been noted as a country with overall low levels of mechanization, low farming productivity, and high crop yield gaps (Boansi et al., 2017). Further, it is estimated that 60 to 80 percent of its population works in the agricultural industry (Mahgoub, 2014) and that agriculture represents about 95 percent of Sudan's exports (Agency, 2009). Despite this, agricultural practices in Sudan remain primitive and require further attention (Mohamed, 2010).

Sudan is also similar and representative of other developing economy countries, particularly in Africa, and the results presented in this dissertation can be more broadly applied beyond Sudan. Kirui (2019) surveyed 9,597 households across 11 countries in Africa and reported that, on average, only 17.5% had access to tractor-powered machinery, which ranged from less than 10% access in the countries Burkina Faso, Cameroon, Ethiopia, Niger, Senegal, Zambia, and Zimbabwe; to a large jump in access in the more developed countries like South Africa (71.9%) and Egypt (90.8%). Identifying feasible opportunities to increase the adoption rates of agricultural technology in these lagging countries could have substantial effects on poverty alleviation (Pamuk et al., 2014).

2.14.1 Agricultural Sector in Sudan

Sudan has a variety of crops that include cereals (wheat, sorghum, millet, corn, and rice), oilseeds (sesame, groundnuts, and sunflowers), beans, chickpeas, lentils, cotton, sisal hemp, and fodder crops. Horticultural crops include vegetables (onions, tomatoes, okra, eggplant, potatoes, watermelon, cucumber) and tropical fruits (Sudan-Ministry of Agriculture, n.d.). The Gross Domestic Product (GDP) for Sudan is represented across three main sectors, where agriculture

represents 32 percent of Sudan's total GDP and 80% of the labor force (Agency, 2013), see Table 8.

Table 8. Sudan's Economy by Economic Sector (Source: CIA World Fact Book 2013)

Sector	GDP	Labor Force
Agriculture	32%	80%
Industry	25%	7%
Services	43%	13%
Total	*100%*	*100%*

Figures 1 and 2 provide a comparison between the US and other developing economy countries in Africa, including Sudan, in terms of agricultural gross domestic product (GDP) and labor force. These figures illustrate the high importance of agriculture in these countries, especially compared to the US. Hence, improvements to crop yield through farm mechanization can have a significant improvement on their GDP and impact on a large portion of the population.

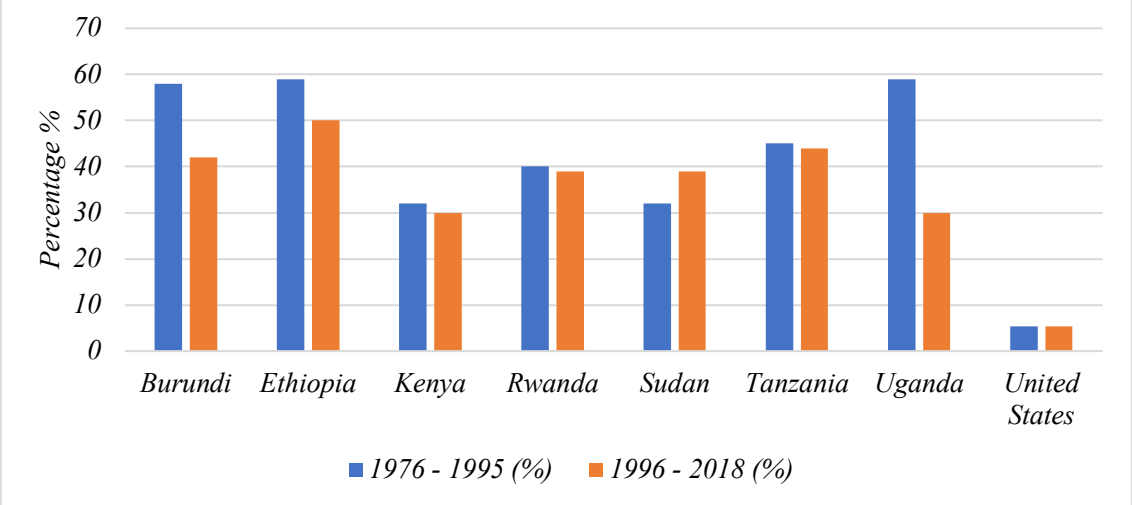


Figure 1. Agricultural GDP as a percentage of total GDP (Source - World Resources Institute 2018)

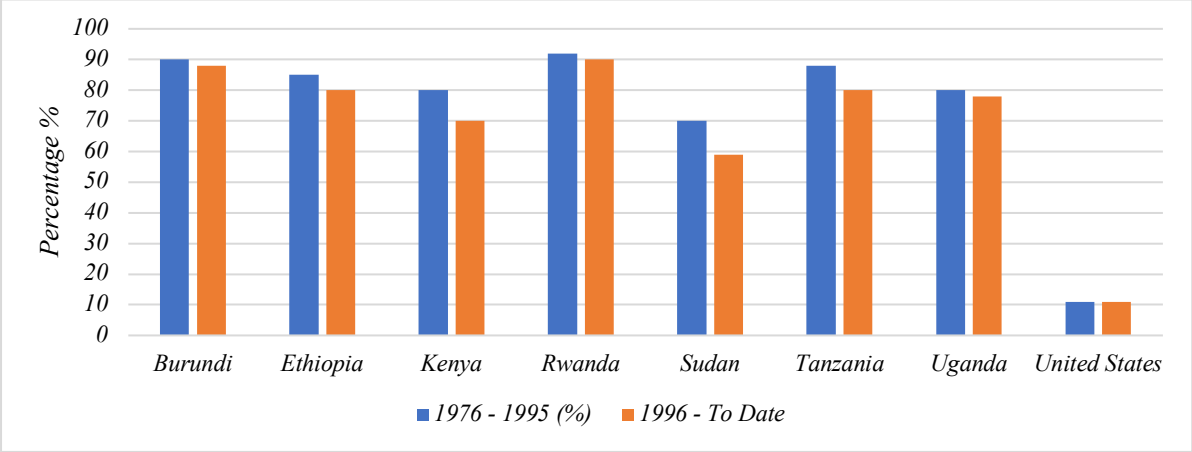


Figure 2. Agricultural labor as a percentage of total labor force (Sources - World Resources Institute 2018, USA Department agriculture, and USA Bureau of Economic Analysis)

2.15 Disadvantages of using Modern Technology in Agriculture:

There are some disadvantages of using the modern agriculture technology in farming. These disadvantages are (Shen, Zhao, Ai, & Ji, 2016).

Reduce the Fertility of the Soil: The soil's fertility is decreased by overusing technology in the fields. One of the worst effects of technology on agriculture is that it diminishes soil fertility. When technology is used excessively, it damages and depletes the fertility of the soil in the fields. While pesticides and fertilizers might speed up output, they also gradually degrade soil fertility. The overuse of fertilizers and several chemicals created specifically for farming can also harm the soil (Yasnolob et al., 2018).

Lack of Education in Farmers: Since most of traditional farmers lack formal education, it can be quite challenging for them to comprehend how contemporary technology is used in farming. They practice traditional farming; using new technology in this setting is particularly challenging for them since they struggle to grasp how to use it safely. Not everyone can easily employ current

technology in farming, which is another drawback of modern technology in agriculture. Most farmers are unable to correctly operate contemporary technological tools and machinery (Shen et al., 2016).

Use of Fertilizers and Pesticides: Numerous issues are brought on by the use of pesticides and fertilizers. The health and productivity of the plant are improved by the use of fertilizers and insecticides. But in some way, it also poses a great deal of issues for both plants and other living things. Overuse of pesticides and fertilizers turns plants and crops into poisons that are dangerous for both humans and other living things. Additionally, it pollutes the soil and water (Sharma & Singhvi, 2017).

High Maintaining Cost: One of the drawbacks of agricultural technology is its expensive maintenance requirements. Small enterprises and farmers find it extremely challenging to control the high technological maintenance costs. Because farmers cannot afford the high maintenance costs of current technical machines and devices, maintaining technology is particularly challenging for them (Kamboj, 2012).

Environmental Damage: The majority of technology tools and gadgets cause climate pollution that is extremely detrimental to us. Tractors, trucks, and other large machinery that are used excessively release harmful chemical gases and carbon dioxide into the atmosphere. Consequently, our environment is contaminated and dangerous for people and other living things. This, in my opinion, is the environmental impact of modern technology that poses the greatest risk (Javadi & Rostami, 2007).

2.16 Gaps in Literature

Much of the previously mentioned research has discussed the importance of agriculture and farm mechanization, particularly in developing economy countries. While this previous work is important, there remains a gap in the literature regarding the incorporation of farmers' needs into the machinery design; including design preferences as well as what they can and are willing to afford. Farming machinery is not a one-size fits all solution, and in particular, farmers with little to no experience with machinery or those in developing economy countries will have different preferences and expectations to adopt this new technology. Further, much of these previous studies have lacked the economic analysis to support adopting farming machinery. Rather, the focus has been identifying the overall benefits and optimizing machinery design for power and energy efficiency.

Hence, this dissertation seeks to quantify the changes in production across various farms and provide statistical support for these claimed benefits of farming machinery. This dissertation also develops a framework for identifying needs and encouraging adoption of farming machinery for traditional farmers in developing economy countries.

In this research, I am utilizing a more HSI approach that focuses on the willingness of traditional farmers in developing economy countries to adopt agriculture machinery as their primary farming practice. While this research is specifically applied to farmers in Sudan, the framework could be applied to other developing economy countries. This study focuses on the human factors behind the adoption of farming machinery and how to encourage traditional farmers to adopt agricultural technology that is reflective of their needs and practices.

This research was likely conducted internally by some farming machinery manufacturers to some extent to study the financial benefits of targeting traditional farmer communities in

developing economy countries, but the goal of this study is to study the traditional farmers' perspective of machinery adoption and to create a framework that connects the traditional farmers and the machinery manufacturers to make adoption more efficient. And then make the study findings publicly available.

As described in the literature review above, the agricultural sector is the engine of sustainable economic growth in developing economy countries. Therefore, it is important to study the adoption of agricultural machinery for the purposes of enhancing the agriculture sector through the lens of human factors. Also, efforts and policies should be directed by the authorities to encourage traditional farmers to adopt agricultural technology that will positively reflect agricultural development and the development of the economy.

Chapter 3

METHODOLOGY

This chapter outlines the methodology used for collecting and analyzing the study data. A treatment control study was conducted in Sudan during the 2019, 2020, and 2021 farming seasons to identify opportunities and barriers for feasibility of farming machinery. This study had approval from the Colorado State University Institutional Review Board (IRB), protocol ID 20-9878H. An individual living in Sudan was hired to travel between the farms, collect data, and coordinate on the Sudan side.

3.1 Participants

There was a total of 36 farms analyzed in this study: 12 ($N_{treatment} = 2$, $N_{control} = 10$) in the north, 12 ($N_{treatment} = 2$, $N_{control} = 10$) in the east, and 12 ($N_{treatment} = 2$, $N_{control} = 10$) in the west regions of Sudan. The farms were selected for inclusion because each farmer used traditional farming practices, meaning they did not use modern farming machinery. The farms included in this study were randomly selected and randomly assigned to either the treatment or control group. The research assistant in Sudan traveled to various villages and asked permission from the tribe leaders to recruit farmers from their villages. There was a total of seven different villages included. Only farms that had similar crops within each region, planting/harvesting schedules, and agronomic practices were recruited. Each of the farms were owned and operated by a different family.

Thirty of the 36 farms, the "without machinery group" (control group), were interviewed about their traditional farming practices in terms of cost, revenue, and net-profits for the 2019 – 2021 farming seasons. The other six of the 36 farms, the "with machinery group" (treatment

group), were provided farming machinery to use over the 2020 and 2021 farming seasons. These six farms were interviewed before using the machinery, about their 2019 farming season, and throughout the 2020 and 2021 seasons about their experience using the machinery for the entire farming process. General information about each farm is provided in Table 9.

Table 9. Demographics of Farms in the Study

Farmer ID	Group	Farm Size (acres)	Location	Hire Labor	Family Members Working on Farm
1	Control	39	East Sudan	Yes	6
2	Control	45	East Sudan	Yes	9
3	Control	43	East Sudan	Yes	5
4	Control	41	East Sudan	Yes	6
5	Control	45	East Sudan	Yes	7
6	Control	35	East Sudan	Yes	7
7	Control	30	East Sudan	Yes	8
8	Control	42	East Sudan	Yes	6
9	Control	50	East Sudan	Yes	8
10	Control	37	East Sudan	Yes	7
11	Control	35	North Sudan	Yes	9
12	Control	36	North Sudan	Yes	7
13	Control	35	North Sudan	Yes	7
14	Control	38	North Sudan	Yes	8
15	Control	44	North Sudan	Yes	6
16	Control	47	North Sudan	Yes	10
17	Control	35	North Sudan	Yes	9

18	Control	20	North Sudan	Yes	6
19	Control	38	North Sudan	Yes	9
20	Control	41	North Sudan	Yes	9
21	Control	56	West Sudan	Yes	11
22	Control	40	West Sudan	Yes	7
23	Control	31	West Sudan	Yes	6
24	Control	44	West Sudan	Yes	6
25	Control	36	West Sudan	Yes	8
26	Control	30	West Sudan	Yes	8
27	Control	25	West Sudan	Yes	6
28	Control	35	West Sudan	Yes	5
29	Control	27	West Sudan	Yes	5
30	Control	29	West Sudan	Yes	6
31	Treatment	120	East Sudan	Yes	6
32	Treatment	100	East Sudan	Yes	9
33	Treatment	56	North Sudan	Yes	7
34	Treatment	91	North Sudan	Yes	8
35	Treatment	56	West Sudan	Yes	6
36	Treatment	61	West Sudan	Yes	6

3.2 Farming Equipment

All Farming machinery was provided at no cost to the participants in the treatment group for use in the 2020 and 2021 farming seasons, where the two farms in each region shared equipment (i.e., one machinery set in the North, one machinery set in the East, and one machinery set in the West). The farms that shared the equipment were located within the same village as each other to enable easy sharing between the two farms. Each region was provided with one set of farming machinery that include a tractor, a cultivator attachment, planter attachment, and harvester attachment. The cultivator is used to prepare the soil before planting, the planter is used to place the seeds into the soil, and the harvester is used to harvest the crops at the end of the farming season. In addition to the tractor and tractor attachments, each farm was trained on how to use the equipment and provided fuel to operate the tractor. All the agricultural machinery, fuel, and training were provided in collaboration with the Food and Agriculture Organization of the United Nations (FAO).

3.3 Interview Structure

All the interview questions were developed in English, then translated into Arabic by one of the members of the research team. The individual living in Sudan who assisted with data collection, conducted all the interviews in Arabic via a script he was provided. After the interviews, a member of the research team translated the interview responses to English. The interviews were conducted with each farmer individually.

All 36 farmers were asked the same questions, plus additional sets of questions for the six farmers who were provided the farming machinery. All 36 farmers were interviewed regarding farming without machinery for the 2019 farming season and about their traditional farming practices, including farm size, crop types, costs, revenues, equipment used, challenges, optimal

machinery design, and their willingness to adopt new farming practices and technology. The subsequent interviews with the machinery (treatment) group focused on costs, revenues, and experiences using machinery, such as challenges, benefits, and changes in farming, while the without machinery (control) interviews focused on costs and revenues. This is described in Table 10. The specific questions asked in each interview is provided in the Appendix of this dissertation.

Table 10. Structure of Interviews for Both Groups

Description	Conducted	Farm Season	Treatment Group	Control Group
Baseline	April 2020	2019	Farming costs and revenues Preconceptions of machinery	Farming costs and revenues Preconceptions of machinery
After Planting	July 2020	2020	Farming costs Experience using machinery	Farming costs
After Harvesting	Sept. 2020	2020	Farming costs and revenues Experience using machinery	Farming costs and revenues
Before Planting	April 2021	2021	Expectations of machinery Changes to farming process	--
After Planting	July 2021	2021	Farming costs Experience using machinery	Farming costs
After Harvesting	Sept. 2021	2021	Farming costs and revenues Experience using machinery	Farming costs and revenues
End of Study	Sept. 2021	2021	Machinery Design Needs	Machinery Design Needs

3.4 Terms Definitions

Some of the machinery design characteristics considered included technical terms. The primary technical terms used are defined as follows:

- *Cultivator Teeth.* they are steel attachments for lifting, loosening, and adding air back into the soil (Selech et al., 2019)
- *Diesel Engine.* Any internal-combustion engine where the air is compressed to a sufficiently high temperature to ignite diesel fuel (Hiroyasu, 1985).
- *Engine Horsepower*. The produced engine power, which is the measure for the engine power to displace 550 pounds of weight one-foot distance in one second, or the power needed to displace 33,000 pounds one foot in one minute (Soechting, 1999).
- *Gasoline Engine.* Any internal-combustion engine in which air is compressed to a sufficiently high temperature to ignite gasoline fuel (Ji & Wang, 2009).
- *Power Take-Off.* Transferring the engine's mechanical power over to another piece of equipment (Li et al., 2017).
- *Transmission.* The device used to change the speed of the engine; installed in the power train between the engine and the driving wheels (Tinker, 1993).

3.5 Data Cleaning and Analysis Methods

The results are divided into three chapters (Chapters 4, 5, and 6), and each chapter utilizes a slightly different analytical approach to address its respective research objective, which are described within each chapter. However, there are several shared approaches in these methods across the three subsequent chapters. As previously mentioned, interview responses were collected in Arabic and a member of the research team that is fluent in both English and Arabic translated the responses. Translations aimed to be as direct as possible between the two languages. All data

cleaning and analysis was conducted using Excel and R Studio. Statistical significance was assessed at $\alpha = .05$. Analytical approaches include hypothesis testing (t-tests and Mann-Whitney U-tests), chi-square tests, Analysis of Variances (ANOVAs) with post hoc tests (Tukey Honest Significant Difference), content analysis, and cost modeling.

Chapter 4

AGRICULTURAL MACHINERY: PRECEPTION OF ADOPTION

4.1 Overview

This chapter explores the qualitative responses of the various responses from this study throughout the 2019, 2020, and 2021 farming seasons. The objective of this chapter was to evaluate current traditional farming practices, initial perceptions of technology, and concerns regarding adoption. Then, evaluate the perspectives throughout the mechanized farming process to identify benefits, challenges, and changes. Lastly, responses at the close of the study were evaluated to understand overall impressions of the farming machinery.

4.2 Methods

This chapter exclusively analyzes the responses of the treatment group, as it follows the shifts in perspective throughout the machinery intervention. First this chapter describes treatment group perceptions before, than after each farming process with the machinery. The interview questions largely elicited open-ended responses, hence yielding qualitative data. A content analysis approach was used to analyze the data. As such, the researchers identified key themes that were repeated between and within the farmers across the different questions.

4.3 Treatment Group Demographics

The average age of the farmers surveyed was 51 years old (SD 4.3 years), and all were males. The average size of the family living on the farm was seven people (SD 1.3 people). The farms in this study were considered small to medium household farms because their land sizes were each relatively small. All the farmers in the beginning of the study (before the machinery

intervention) stated that they hire extra laborers, both during planting and harvesting, because their families cannot do all of the farming work by themselves. Farmers in the different areas of Sudan farm different types of crops due to differences in weather, water resources, and, most importantly, local traditions. In half of the farms, only the male members of the family worked on the farm. This is summarized in Table 11.

Table 11. Farm Characteristics for Treatment Group

Location	**Size,** *acres*	**Crops**	**Family Working on Farm,** *N*	**Hire Labor?**
North	91	Peanut, Potato, Wheat	4 (males only)	Yes
North	56	Potato, Wheat	6 (males only)	Yes
East	100	Cucumber, Eggplant, Okra, Tomato	6 (all genders)	Yes
East	120	Carrot, Eggplant, Green Pepper, Okra, Potato, Tomato	14 (all genders)	Yes
West	63	Peanut, Sesame, Watermelon Seeds	5 (males only)	Yes
West	56	Peanut, Sesame, Watermelon Seeds	6 (all genders)	Yes

4.4 Traditional Farming Practices [Before Machinery]

All of the farmers described their current farming practices as rooted in their culture and lifestyle; describing it as having worked for generations before and hence not seeing a need to change. When asked how long they had been farming, all mentioned they had "inherited the land." Four specifically said their father had been a farmer, one said their grandfather and one said their family had been farmers for hundreds of years. While all of the participants said they would not give up farming or their land, two farmers mentioned that their sons were considering moving to the city to pursue another way of life and a third farmer mentioned their neighbors considering the same. None of the participants used modern technology for farming practices but expressed satisfaction with using cows and horses instead, see Table 12.

Table 12. Themes for Traditional Farming Practices

Question	Key Themes	Supporting Quotes
Why do you think farmers use traditional techniques over machinery?	Culture (N = 6) How they learned to farm (N = 6)	• "They are doing this job for a long time. It's our way of life, and we are ok with it." • "All people in this area are using the same farming process. It's traditional in this area, and people just follow their culture. But, if I am going to make a decision, I will keep it that way. I believe we have a healthy and safe environment." • "We don't know other than this. We saw our parents doing it, and now we are doing what we taught."
Have you considered quitting farming and	No (N = 6) But younger generation	• "No, No. That will never happen. The land is more important than anything. We will fight and die for our land."

switching to something else?	considering this (N = 3)	• "No never. Yes, it is a hard job, but I am happy with what God gives me. I will not give up my land for anything, and I will teach my kids to take care of it." • "I have not thought about that. I am very satisfied with the way I am living my life. But my oldest son always wants to quit farming and go to the city to find something else to do. He is a smart person, and I think I will allow him to go." • "Because of the increasing cost, some of my neighbors are thinking about giving up their land and finding something else."
Do you currently use any farming machinery?	No (N = 6) Use cows and horses (N = 5)	• "I have never thought of using one." • "Machinery comes with its own complications such as maintenance, fuel, tax." • "We have our way in farming, and I think we don't have any problems with that."

While it is difficult to influence change in a behavior based on tradition and for people whose lives are built around this culture, it was apparent that younger generations would likely be more accepting of technology. The farmers in this study ranged between 47 to 58 years old, but two of them mentioned their sons were seeking an alternative lifestyle and several of the farmers mentioned that their children were pleased by the use of machinery in this season's planting process. This suggests a potential shift in future generations' willingness to accept farming technology at a higher rate than Africa is currently experiencing.

4.5 Challenges with Traditional Farming [Before Machinery]

Participants were asked, "What problems do you usually face in farming," see Figure 3. The common responses across farmers were availability of resources (labor, fertilizer, diesel), security threats, and difficulty selling products at a good rate:

1. *Costs.* Increasing costs associated with traditional farming practices, predominately labor, have been rising faster than returns on the crops.
2. *Labor.* Not enough laborers to hire or too expensive to hire laborers. Farms in the western region of Sudan reported difficulty finding workers to hire because the area is considered too unsafe. Due to the labor challenges, farmers reported not being able to harvest their crops on time and, as a result, losing part of their crops.
3. *Fertilizer.* No access to fertilizer or too expensive to buy. Farmers would overcome this by burning the land so that the resulting carbon would fertilize the land. Farmers reported the insufficient fertilizer leading to low crop production.
4. *Security [Militia].* Militia fighting in the area would invade villages and loot farms during harvesting season to feed their soldiers.
5. *Selling Product.* Without access to markets and city centers, farmers are unable to sell their products and forced to sell to brokers at an unreasonably low price.
6. *Diesel.* Difficulty finding diesel for their water pumps leads to over-priced black-market prices or portions of the land unfarmed.

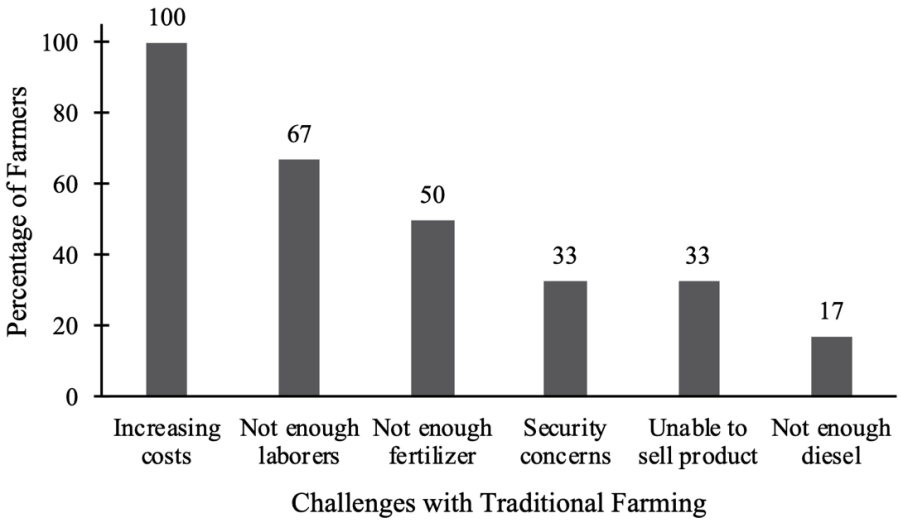


Figure 3. Reported problems with current farming practices

These key challenges are further detailed in Table 13, which provides examples of the farmers' explanations to these topics.

Table 13. Key Challenges in Traditional Farming

Challenge	Farmers Mentioned, *N (%)*	Supporting Quotes
Labor: not enough or too expensive	4 (66.7%)	• "Some years, I have seen the production wasted because it was not harvested on time." • "We cover that by asking help from family and neighbors, but still, that's an issue, especially in the last few years." • "Sometimes we can't find workers to hire because everyone thinks this area is not safe, so they don't want to come to work around here."
Fertilizer: not enough	3 (50%)	• "Sometimes we burn the land. So the carbon can fertilize the land."

		• "The needed fertilizers will not be available in the market, so we will just plant without it."
Security: militia	2 (33.3%) * Both farms in West	• "Sometimes, the militias will come from Darfur and attack us during the harvesting season to tackle our production so they can feed their soldiers. I have seen this happening four times, and two people were killed in this area because they said no." • "Sometimes, the militias who are fighting the government will invade our village and loot our harvest. This happened three or four times, and the government can't do anything about that; in these incidents, we lost a lot. And every time we hear there are some militias moving around. We get scared."
Product: can't sell	2 (33.3%)	• "And the only thing we can do with that is to lower the price so we can sell." • "The brokers sometimes give us a very low price for our products, and we have to sell to them because there are no other options."
Diesel: not enough for water pump	1 (16.7%)	• "One of the issues is to find the diesel for the water pump that is feeding the land. So, we had to buy it from the black market."

All of the farmers indicated concern regarding the increasing costs of traditional farming practices, which have been rising faster than returns on the crops. Without machinery, traditional farming requires a significant number of human labor hours, which makes labor the primary cost for farmers. When asked about the price of labor over the past few decades, the average cost of a single worker in the year 2000 was 50 SDG per acre and 1000 SDG per acre in 2020, which represents a 1900% increase. Over the past five years, farmers reported an average increase in labor of 27% per year (300 SDG per worker per acre to 1000 SDG per worker per acre in 2015 to 2020). On average, farmers reported that 40% of their planting costs and 65% of their harvesting costs were labor expenditures.

Moreover, all of the farmers described inconsistent returns year over year for crops. In fact, all six of the farmers said that in recent years they had at least one season where expenses were higher than profits. In addition to the increasing cost of labor, the farmers referenced seed availability, agricultural pests, rain percentage, market proximity, and transportation as the other major factors affecting their profit margins. Due to a lack of access to [reliable and affordable] transportation, all of the farmers described having to sell their products to a local broker, who would buy at a very low price, and then transport the product to the bigger cities and sell at a high price, making the profits high for the broker, but low for the farmer. The farmers described this relationship between the broker and farmer as very dissatisfactory.

A common challenge across all farmers was recovering profit margins, where all described at least one recent season where they were not able to at least break even. Similarly, Boansi, Tambo & Muller (2017) reported a low productivity of crop fields in Sudan and a need for farmers to be more resilient. In our study, labor was found to be the primary source of farming costs, due to the fact that traditional farming is highly labor intensive. This was supported by the farmers reporting

that 40% and 65% of their planting and harvesting expenditures, respectively, were on labor. Not only were labor rates high and rapidly increasing over the past few decades (i.e., 27% per year over the past five years), but farmers reported insufficient available labor, with two farmers saying they had seen crops wasted because there was not enough labor available to harvest them in time. Adoption of farming machinery could have an immediate impact on profit margins, as the machinery could help reduce the number laborers needed.

Another shared challenge by the farmers was selling their products at a fair price. Farmers reported having to sell their products to a local broker, who would undermine the farmers by forcing them to sell their products for a very low price. Then, the broker would transport the products to bigger cities where they were able to sell the products for much higher. This is a common issue in traditional farming, where the lack of access to transportation limits farmers' ability to sell their product directly to the end-user (Thurston, 2019). In an effort to remedy this, Boansi, Tambo & Muller (2017) suggested policy makers should contribute towards improving farmers' access to markets. While farming machinery could help lower the cost of production, farmers would still be vulnerable to the controlled prices set by the brokers. An additional opportunity for technology to improve conditions would be to solve the issues related to market accessibility.

4.6 Willingness to Adopt New Technology

Participants were asked various questions regarding what farming machinery they would like to use or would be willing to use, see Table 14 and Table 15. All of the participants said that they were unfamiliar with farming machinery but wouldn't buy machinery regardless; citing the headaches that maintenance causes and the unnecessary/extra features available on modern machinery. While all were willing to try new machinery if given the opportunity for free, they were concerned it might ruin their crops, make them a target to the militia, disrupt their culture, and would first need approval from their tribal leader.

Table 14. Themes for Interest in New Technology

Question	Key Themes	Supporting Quotes
Are there any farming technologies you would like to use?	Not familiar with technology (N = 6) Content with current farming practices (N = 6)	• "I have heard people talking about it, but I don't know what that is." • "But I believe I have enough farming experience to make me a good farmer." • "But we are experts as farmers. We know what to do to farm, and we know what we want."
Can you afford to buy any farming machinery?	No (N = 6) Owning machinery comes with	• "I don't feel I need any farming machinery, but even if it's available, I don't think I will afford to buy them. Also, I have seen some of this machinery that has a lot of things that we don't need. For example, some of the tractors are very

	too much extra hassle (N = 6)	expensive because they have some added features (speaker, Bluetooth, daylight head beam). We don't care about such features; we just want to see something that will work in the land." • "I don't know how much this machinery cost, but I don't think I will buy it. I have this lifestyle, and I think I will just continue to live like that." • "I am afraid of the cost. I am worried about that. I know there will be maintenance and fuel cost. Maybe I need to pay tax for the machinery. I am not ready for this headache yet." • "I don't think I can afford to buy one, and even if I can, I don't think I will buy it because, as I said, I don't want to be a target to the thieves and the militias. They will think I am a rich man; then, they will attack me. There were some incidents when some farmers bought cars, and they have been attacked by the militias, and they took the cars from them. So, it is better to be like everybody in the area."

Table 15. Themes for Willingness to Adopt Technology Given the Opportunity

Question	Key Themes	Supporting Quotes
If I suggested new technology that might help you improve, would you use them?	*(N = 6)* Willing to try only if it truly improved the process	• "Well, if, as you said, it is going to help, then it is ok but, don't destroy our farming season." • "Yes, sure, I want to get better in farming operations, but also, I can't afford to destroy my farming season. If what you are going to suggest is going to help in improving the process, then yes." • "Yes, sure, but I will need to make sure that it does not have any negative effects on anything around me."
If you were given a chance to use machinery, would you accept it?	*(N = 6)* Willing to try, but skeptical	• "Well, I might try, but I will not make it the way of my farming process forever. I will still continue to use my horses. Because I like my culture, and I don't want to give up my culture for modern machines. A peaceful life is very important to us." • "I am open to trying new things as long as it is going to help. So, it's yes, I will accept it. But I am afraid that these militias will hear that I am using machinery, and then they will think I am a rich person, then I will be targeted by them." • "I don't know, but I don't see any reason not to accept it."
We are planning to provide you with machinery,	*(N = 6)* Yes, but need permission from a local authority	• "Ok, I will accept that as long as it is going to help me and if it is not going to harm the land. Also, we need to talk to the tribe leader before we do so." • "Well, why do you want to help us? Ok. That is something I have never tried, but I am ok to try it."

will you accept it?	• "I don't mind, but before that, I will need to make sure that my tribe leaders are ok with that." • "Yes, of course, I will try the machinery and hope it will be good."

At the beginning of this study, farmers reported having minimal to no knowledge of modern farming machinery. They were reluctant to think machinery would improve their farming practices, with the following themes evident in their responses: *(1)* traditional farming has worked for generations and thus there is need to change; *(2)* their culture and environment are important, and machinery would interfere; *(3)* owning machinery would lead to too many complications such as maintenance, spare parts, and fuel; and *(4)* owning machinery would cause militia to perceive them as rich and as a result target them. This overall lack of experience and knowledge was also described by Bello (2014), who reported that agricultural extension services (i.e., farming innovations that increase food production, such as machinery) reach only a limited number of farmers in Sudan.

4.7 Synthesizing Perceived Benefits and Challenges

A summary of the common themes shared across farmers in terms of benefits and challenges that both traditional and modern technology offer in farming practices is provided in Figure 4.

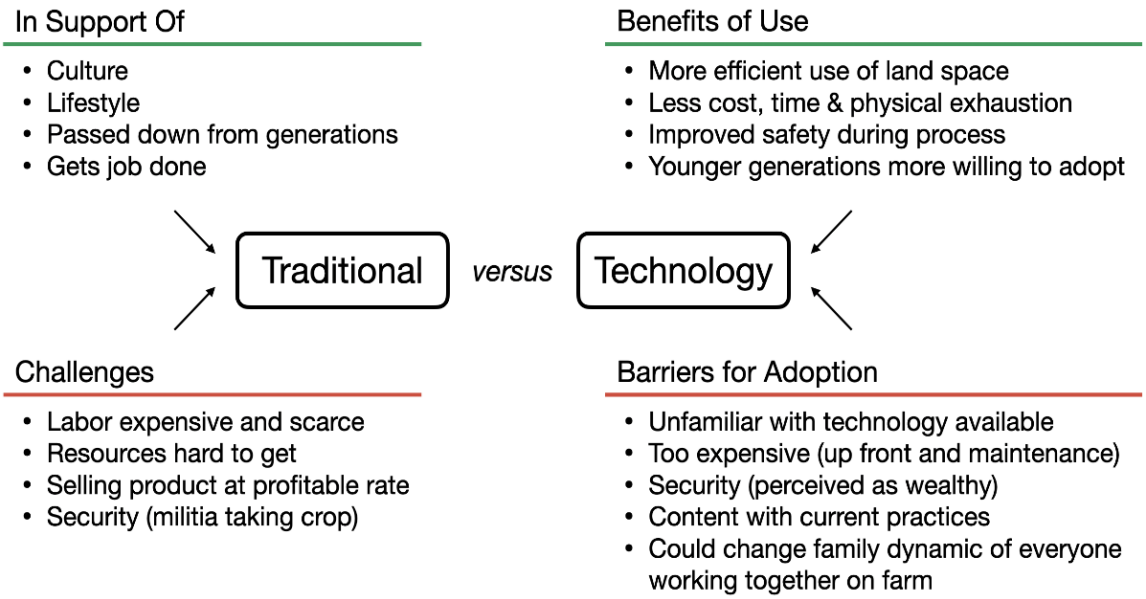


Figure 4. Benefits and barriers to technology adoption

4.8 Machinery Impact: After Planting in 2020

The treatment group were interviewed after they used the farming machinery for planting operations for the first time. The questions are related to farmers' previous experiences of using traditional farming to their experience using farming machinery in planting operations. The farmers' response's themes were focused on the impact of using the farming machinery for the first time in the planting operation.

All the farmers expressed an overall positive attitude towards the machinery, see Table 16. The time it took the farmers to plant their crops was reduced from an average of 4.1 weeks (SD 0.6) without the machinery to 5.6 days (SD 1.1) with the machinery. All of the farmers also said the

machinery reduced the cost of planting compared to previous seasons, by reducing expenses, time, and physical effort. The primary cost with the machinery was just purchasing seeds. Additionally, all of the farmers said the machinery reduced the number of laborers needed, where none of the farmers needed to hire any laborers, which was a rarity for all of the farmers. Two of the farmers even mentioned that their children, horses and cows seemed happier not having to do the physical labor.

Table 16. Experience Using Machinery for Planting

Question	Key Themes	Supporting Quotes
What is the difference between planting this season (with machinery) and previous seasons (without machinery)?	Less cost (N = 6) Less time (N = 6) Improved safety (N = 6) More efficient land usage (N = 6)	• "I like the way the land was prepared; it was easy and fast. Also, it was a very smooth process. I would say the big difference was in the time and the spacing between each line of the plants. They are organized, and the space is small." • "We used most of the land space. The time was way less compared to using the cows and manpower. Usually, we get some incidents of snakes biting us, but now we don't have any of that. Even the cost is way less compared to the previous season." • "The obvious difference was the time and the cost. Less time and less cost." • "It was different; especially the timing was very different. We used to spend a long time on planting, but with the machinery, it is a very short time. Also, the cost was less, and no workers needed."

Are you satisfied with the machinery?	Yes, very satisfied (N = 6)	• "I am very satisfied with what happened. These machines made me and my family happy." • "Yes, very satisfied, but I am worried that I get used to it, and then next season, I have to go back again to what I was doing previously." • "Yes, I am very satisfied. The machinery released a lot of stress out of my shoulders. And I think this machine can make us plant well."
Will you use the machinery next season?	Unsure, improved process but concerned about impacts and maintenance (N = 6)	• "I think it's a good idea to use machinery in farming. It's very efficient, but it will make us jobless, and I am afraid most of the younger generation will leave us to find work in the big cities, which is something I don't like. I want all my family members to be together. But I think it's good to use the machinery in the farming process." • "I will think about that seriously and see if I can do it." • "If it's something easy to use, I will use them. But I am worried about the price, the maintenance cost, and the fuel availability. For now, we can manage our life using our cows, but with the machinery, we don't know how we can overcome its issues. But I will use it if I can." • "I will consider it, but as I mentioned, I will put myself in the focus of the bad people, but if the security issues were solved definitely, I would consider using machinery."

- "I will think about that, but the decision will include all members of my community. But, from my side, I will support using machinery in farming. But hopefully, that will not be a reason for the militias to invade our villages."
- "I have tried it, and I think it's a good idea to consider using this machinery but, there are few things that need to be done before that; I am part of a community (tribe). We all need to agree on using these machines. The price for it needs to be affordable. The logistics like maintenance and fuel are also a factor. But I think using it would have a positive impact if we solved its side issues."

However, there were still concerns expressed by the farmers regarding the negative impacts of long-term machinery adoption, such as: (1) Machinery will replace farmers, causing the younger generation to leave family farms for the city life; (2) Machinery prices, maintenance costs, and fuel availability are still prohibitive; (3) Machinery ownership will cause the militia to think that the farmers are wealthy and lead to more problems; and (4) Machinery adoption should be discussed at the community level rather than at the individual farm level.

4.9 Machinery Impact: After Harvesting in 2020

The "after harvesting season" consisted of seven questions related to their experience and expectations of using the farming machinery in harvesting and compared the amount of products and the return to the previous farming seasons. All of the farmers expressed an overall positive attitude towards the machinery, see Table 17. The time it took the farmers to harvest their crops was reduced from an average of 3.75 weeks (SD 0.41) without the machinery to 5.16 days (SD

1.1) with the machinery. All of the farmers also said the machinery reduced the cost of harvesting compared to previous seasons by reducing expenses, time, and physical effort. Additionally, all of the farmers said the machinery reduced the number of laborers needed, where none of the farmers needed to hire any laborers, which was a rarity for all of the farmers. One farmer mentioned that he felt relief because he didn't need to hire any labor because last season, he couldn't harvest all of his land because he couldn't find enough laborers to be hired during the harvesting season, which made him lose some of his production, and the harvesting time last more than a month.

Table 17. Experience Using Machinery for Harvesting

Survey Question	Key Themes	Supporting Quotes
What is the difference between harvesting this season and the previous seasons after you use the machinery?	• No Labor issues / No need for labor (N=6) • Harvesting was done on time (N=6) • Less time (N=6) • Less cost (N=6)	• We were not worried about finding laborers to harvest for us. • We were able to organize the harvesting operation in a timely manner. • Harvesting time was way less compared to the previous seasons.
Does the machinery have any effect on the production amount?	Yes, we have more products amounts (N=6)	Yes, the amount of harvest is more compared to the previous seasons. And I believe because the machine plants the corps in an organized way, what increases the planted

		spaces—also, the harvester harvests all the plants.
Will you use the machinery next season?	Yes, improved process, make the farming process much easier (N=6)	I don't see any reason why I won't use them. It was very helpful.
Are you satisfied with the harvesting process using the machinery?	Yes, very satisfied (N=6)	Yes, I am very satisfied. I think as farmers, we should think about improving the farming process using machinery.

4.10 Machinery Impact: Before Beginning of Second Mechanized Farming Season [2021]

For the 2021 farming season, the "before planting season" interview had eight questions relating to the farmers' previous season (2020) planting practices (i.e., with using farming machinery), including the positive and negative points about using farming machinery, equipment used, challenges with using the machinery, and if they were willing to adopt this farming practices/technology for their future farming, also, if they have any suggestion for the way the farming machinery should be used. All of the participants said that they don't want to see any difference in using farming machinery this season, and they want to see the same performance with machinery in comparison with the 2020 farming season. All of the farmers said the positivity of using farming machinery is reducing the cost of operations compared to traditional farming by lowering expenses, time, and physical effort, Farming machinery helped them farm the entire farmland area, and the operations were very smooth, and they believe there is no change needs to be made with the way they use the machinery because it addressed all their initial concerns. On the other hand, one farmer believes that the negative point of using the farming machinery is that

they had to change their farming calendar because using farming machinery reduces the operations time compared to traditional farming.

Traditional farmers indicated that they didn't have any issues using the machinery for the previous farming season. Still, they have some challenges when they use the machinery when random people that they don't know or some of their community members approach them and ask them for information about farming machinery. They don't have enough knowledge to answer any questions about them. They also indicated that one of the main challenges is that the older people in their community didn't like changing the culture in trade to the farming machinery.

Traditional farmers were able to operate the machinery by themselves, and they indicated that as an easy operating process and they indicated that they thought about owning farming machinery and started as a community talking more about the benefit of using or owning the farming machinery and convincing old people with the benefits using farming machinery. Other farmers went even more than that by talking to local financial institutions about financing options if they decided to own any type of farming machinery. See Table 18.

Table 18. Expectations before the beginning of the second farming season

Survey Question	Key Themes	Supporting Quotes
What do you wish to see different this time? Or what suggestions do you have?	• Want the same performance as last season (N=5) • More familiar with the Machinery (N=1)	• I really want to see the same performance with Machinery in comparing with the last season. • I need to know more about operating the Machinery

		and the actual cost to operate them.
What do you think is the positive point of using machinery before the planting season? And what are the negative points?	Positive: • Less time (N=6) • Less cost (N=5) • Farm entire land (N=2) • Smooth operation (N=2) • Less physical effort (N=1) Negative: • Need to change farming schedule (N=1)	
Have you faced any challenges after the previous season?	• No issues at all (N=5) • Random people will come and ask about farming machinery (N=1) • Older people didn't like changing the culture (N=1) • No knowledge to answer any questions about farming machinery when asked by other community members (N=1)	• Last season was very smooth with a good return. The only issue was I need more knowledge about operating the farming Machinery. • The challenge was from my community; They wanted to know more about the Machinery, but I

		didn't have the answer for them.
Are there any changes that you want to address this farming season?	• No change is needed (N=5) • I would change the start time for the farming process because, with machinery, there is no need for more time before the start of the farming process (N=1)	I don't need to change anything, but instead of giving the land preparation a month of time, I will give it ten days. Because preparing the land from the last season took less than a week.
Has the machinery addressed your traditional farming concerns?	• Yes, it did address all the farming concerns (N=6) • Have a concern about the safety issue (N=2)	Yes, we were concern that the Machinery will affect our farming season, but actually, it was good, and all our concerns were eased.
Regarding the land preparation process, do you think the machinery prepares the land better, or the traditional technique is	Machinery prepares the land better than traditional practice (N=6)	Yes, all the issues related to farming were addressed.

better in preparing the land? Why?		
Have you thought about owning farming machinery to do the land preparation? If yes, what steps did you take to do so?	Yes, I have (N=6)	• As a community, we were talking more about the benefit of using or owning farming Machinery. • Convincing older people to use farming machinery. • Talking to the local authority about financing farming machinery.
Did you operate the farming machine during the land preparation operation? If so? How easy was it to use (scale of 1 to 5)? If you didn't operate it, would you be willing to learn how to operate it?	• Yes, I operated them myself (N=6) • It was easy to operate (N=6)	

4.11 Machinery Impact: After Planting in 2021

Five questions were asked to the treatment group (with the machinery group) after they used the farming machinery for planting operations for the second. The questions are related to farmers' previous experiences of using farming machinery in the planting operation of the 2020 farming season. The farmers' response's themes were focused on the differences between using farming machinery in farming operations for two seasons, as all farmers didn't see any difference in the planting operations between the two farming seasons when they used the farming machinery. The response focused was in the following points Table 19:

Table 19.Experience Using Machinery for Harvesting

Question	Key Themes	Supporting Quotes
Is there any difference between planting this season and last season? If yes, what are the differences?	No differences (N=6)	• I don't see any difference in the planting operations at all. • I would say it was very much the same as last season.
Was the planting time the same as last season?	Yes, it was same (N=6) Some delay in the starting time	• Yes, the planting time was almost the same as the last season. It was about 6 days. • Yes, the planting time was not different; there was some delay because there was a need for diesel, and that made us wait for one day to

		get it. But the actual operation time was the same as last year.
What about the cost of planting in comparison to last season?	• The cost is same (N=1). • Increase the seeds price (N=5).	• For me, I had to pay only for the seeds like last year. But the seeds price went up almost three times more. • The cost was more because of the increase in the seeds price. It was almost three times more. • Last year my cost was buying the seeds, and the seeds price almost tribble this season compared to the last season. And I think that because the government has freed the exchange market and made the official market the same as the black market. And the exchange rate went up from almost 255 Sudanese pounds per one US dollar to around 500 pounds per one US dollar.
Have you faced any issues using farming machinery in this planting season?	No Issues. (N=6)	There were no issues in using the farming machinery at all. Everything was smooth, exactly like last season.

· Did you operate the farming machine during the planting operation? If so? How easy was it to use (scale of 1 to 5)? If you didn't operate it, would you be willing to learn how to operate it?	• All operate by themselves (N=6). • Easy to use. (N=6).

However, there were still concerns expressed by the farmers regarding the availability of the machine fuel as there were one day delay from the set starting date.

4.12 Machinery Impact: After Harvesting in 2021

Twenty-eight questions were asked to the treatment group (with the machinery group) after they used the farming machinery for harvesting operations for the second season and using the farming machinery for two farming seasons. The questions are related to farmers' previous experience using the farming machinery in harvesting for the second time and measure the consistency in the amount of production and return when using harvesting machinery also, related to farmers overall view of using the farming machinery. The farmers' response's themes were focused on the differences between using farming machinery in farming operations for two seasons, as all farmers didn't see any difference in the harvesting operations between the two farming seasons when they used the farming machinery. Also, farmers have strong desire in finding a way to use farming machinery in their future farming operations. The response focused was in the following points:

4.12.1 Reflection on Overall Experience Harvesting with Machinery

Part of the asked questions were related to the farmers harvesting experience for the second time. The farmer's responses were as follow in Table 20.

Table 20. Questions related to the harvesting operation

Question	Key Themes	Supporting Quotes
How did the harvesting operation go this season?	No differences (N=6)	The harvesting for 2021 farming season went with no issues for all farmers.
Are there any issues with harvesting using Machinery? If yes, what are these issues?	No issues (N=6)	Harvesting for the 2021 farming season went with no issues or disturbance for farmers
Has the return similar to the previous season? What are the differences in percent compare to last season?	Very similar (N=6)	The farming return for the 2021 farming season was very close to the farming return for the 2020 farming season.
What about the harvesting cost and harvesting time in comparison to the last season?	No different in harvesting time (N=6) Different the harvesting cost (N=6)	The harvesting time for the 2021farming season was similar to the last season's 2020 farming season. But the harvesting cost was different because of the change in the exchange rate to the dollar between the 2020 and 2021 farming seasons.

4.12.2 Reflection on Overall Experience Using Machinery

Part of the asked questions were related to the farmers experience of using the machinery for the second time. The farmer's responses were as follow Table 21:

Table 21. Questions related to the experience of using machinery

Question	Key Themes	Supporting Quotes
Are you satisfied with using Machinery in the last two seasons?	Very satisfied (N=6)	All farmers expressed satisfaction with using the farming machinery for the last two seasons.
How much farming cost do you think the Machinery will save?	• Saved labor cost (N=6) • Saved time (N=6)	The farmers stated that, farming machinery saved all the labor cost and all the extra time for farming operations.

4.12.3 Reflection on Changes in Willingness to Adopt Farming Machinery

Part of the asked questions were related to the farmers willingness to adopt farming machinery in their farming operations. The farmer's responses were as follow in Table **22**.

Table 22. Farmers Willingness to Adopt Farming Machinery

Question	Key Themes	Supporting Quotes
Are you going to own farming machinery? And what's your plan to do so?	• Thinking seriously about owning farming machinery (N=6). • Start to explore owning options (N=6).	All farmers indicated that they would think seriously about owning farming machinery and will start exploring all the options (Finance, shared, ...).
Have you faced any security challenges with using farming Machinery?	• No security issues (N=4) • Security concern (N=2)	The farmers who are located on the east and north side of Sudan indicated that they had no security issues. But the farmers from the western part of Sudan said they were anticipating something to happen because of the unstable nature of the western part of Sudan But, luckily nothing has happened to them.

Have you faced any social challenges with using farming Machinery?	People questions and curiosity about machinery (N=6).	Yes, many local farmers wanted to know how to get farming machinery to use in the farming process. Also, the farmers would need to explain to them about this study. Another group of people would ask about the usefulness of using the farming Machinery in the farming process.
Has anyone in your community expressed interest in using the farming Machinery and owning them? Is there any community-organized effort to own farming machinery?	Yes, many people have interest in using machinery (N=6).	The farmers talked to many people who showed interest in using and owning farming machinery after they say how farming machinery can be useful.
Have you had any contact from the local authority regarding this two-seasons farming practice? If yes, what was it about?	No contact with authority (N=6)	
How did you use the extra time that you had during that last two seasons?	• With family (N=6) • Connection with community (N=2) • Taking care of their animals (N=4)	The farmers spend the extra time around their families, around Community, taking care of their animals

What is your overall idea about using farming machinery over traditional farming operations?	• Safe time (N=6) • Safe money (N=6) • Less effort (N=6)	Before using farming machinery, farmers have no idea about farming machinery but after trying them farmers think farming machinery has many positive things that traditional farmers should consider such as low cost, less time, and less effort.
If you think using Machinery instead of traditional farming is good, what is the best way to address this point to the rest of the community?	By addressing the impact of machinery (N=6)	The farmers believe the rest of their community will be convinced when they see the different that the farming machinery mad in the last two season for farmers who used them.
Do you think there are any barriers that will prevent you from owning farming machinery? If yes, what are these barriers?	• Finance barrier (N=6) • community and tribes' approval (N=6)	The farmers think that the only barriers are finance and getting their community and tribes approval.
If the farming Machinery would be shared between farmers, how many families do you think	Four families (N=6)	The farmers believe that farming machinery can be shared

could share the farming equipment?		between at least four families with 25% share for each family.
On a scale of 1 – 5, what is the probability that your community will consider using farming Machinery? With; 1) No Chance. 2) – Neutral. 3) Hight Chance 4) Very Hight Chance	Neutral (N=2) Hight chance (N=4)	

On a scale of 1 – 5, how likely are you going to use the farming Machinery (Figure 5)? With;

1)Extremely unlikely. 2) unlikely. 3) Neutral. 4) likely. 5) Extremely likely.

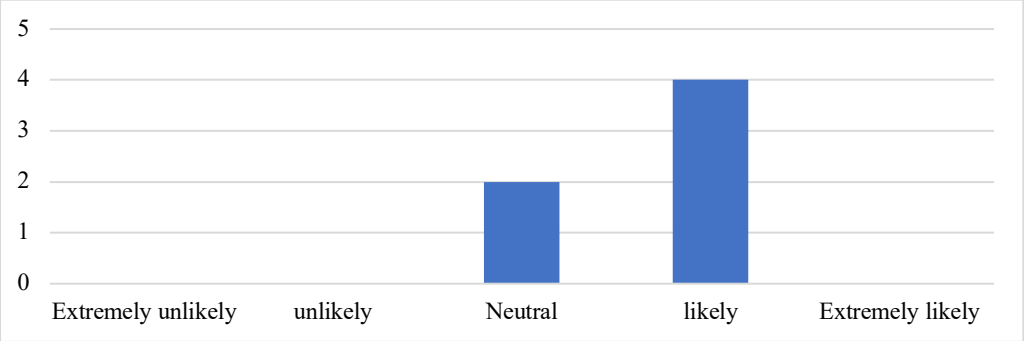


Figure 5. Likely of using farming machinery

4.12.4 Reflections on Impacts of Farming Machinery

Part of the asked questions were related to the impact of farming machinery in farmer's life and farmer's way of farming. The farmer's responses were as follow Table 23.

Table 23. farming machinery impacts

Question	Key Themes	Supporting Quotes
What was the impact of using the farming Machinery on your lifestyle and your family?	• More relax (N=6) • less physical work (N=6)	The two major impacts that farmers indicated are: (1) Machinery made Farmers more relax because they knew that the operation will be done within the time. (2) less physical work for farmers and their family member.
What farming tasks do you think are important to use the Machinery for? Or What farming tasks would you rather not use the Machinery for?	All farming tasks (N=6)	
how did the use farming machinery affect you and your lifestyle? with	Make my life easier (N=6)	

On a scale of 1 – 5, how do you find the farming Machinery helpful in land preparation (Figure 6)? With;

1) Not helpful at all. 2) Not helpful. 3) Neutral 4) helpful 5) very helpful

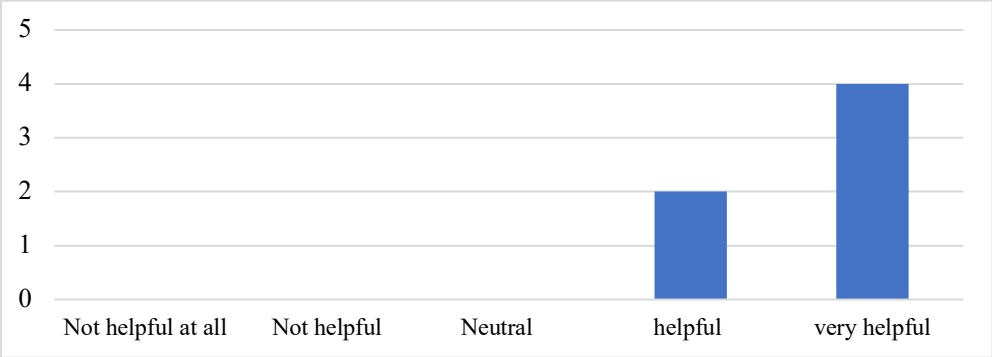


Figure 6. Machinery helpfulness in land preparation

Did you operate the farming machine during the Harvesting operation (Figure 7)? If so? How easy was it to use (scale of 1 to 5)? If you didn't operate it, would you be willing to learn how to operate it?

1)Very complicated. 2) complicated. 3) Neutral 4) Easy 5) very Easy

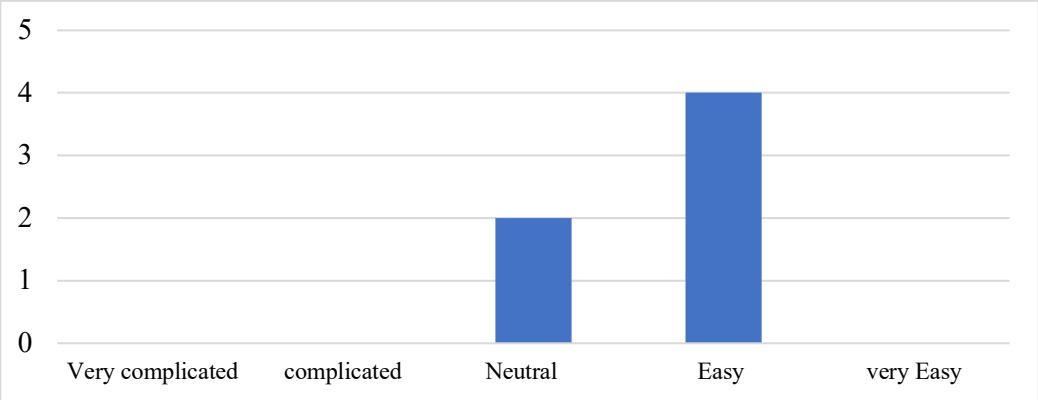


Figure 7. How easy was using farming machinery

On a scale of 1 – 5, how do you find the farming Machinery helpful in planting operations (Figure 8)? With;

1)Not helpful at all. 2) Not helpful. 3) Neutral 4) helpful 5) very helpful

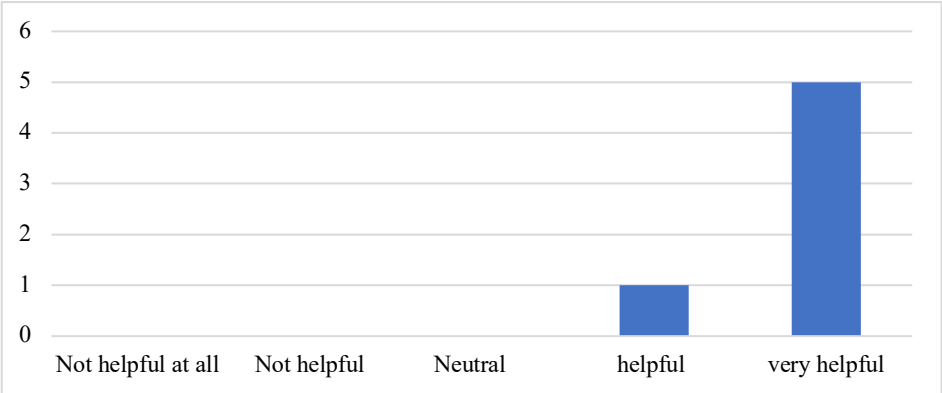


Figure 8. Machinery use in planting operations

On a scale of 1 – 5, how do you find the farming Machinery helpful in crop harvesting operations (Figure 9)? With;

1)Not helpful at all. 2) Not helpful. 3) Neutral 4) helpful 5) very helpful

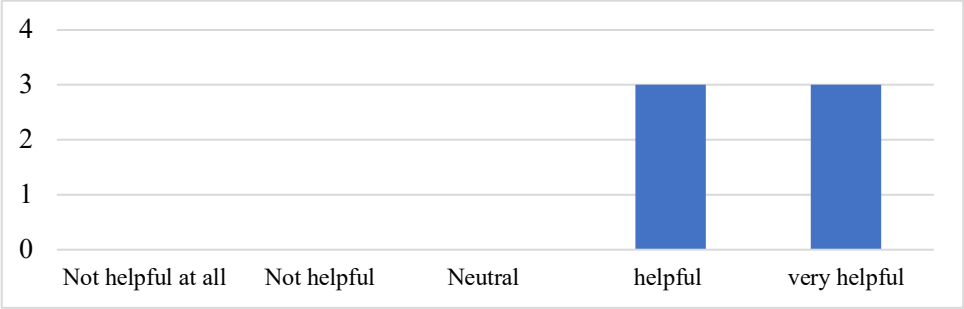


Figure 9. Using machinery in harvesting

4.13 Chapter Summary and Discussion

All of the farmers described their current farming practices as rooted in their culture and lifestyle; describing it as having worked for generations before and hence not seeing a need to change. While it is difficult to influence change in a behavior based on tradition and for people whose lives are built around this culture, it was apparent that younger generations would likely be more accepting of technology. The farmers in this study ranged between 47 to 58 years old, but two of them mentioned their sons were seeking an alternative lifestyle and several of the farmers mentioned that their children were pleased by the use of machinery in this season's planting process. This suggests a potential shift in future generations' willingness to accept farming technology at a higher rate than Africa is currently experiencing.

A common challenge across all farmers was recovering profit margins, where all described at least one recent season where they were not able to at least break even. The low productivity of crop fields in Sudan and a need for farmers to be more resilient. In our study, labor was found to be the primary source of farming costs, due to the fact that traditional farming is highly labor intensive. This was supported by the farmers reporting that 40% and 65% of their planting and harvesting expenditures, respectively, were on labor. Not only were labor rates high and rapidly increasing over the past few decades (i.e., 27% per year over the past five years), but farmers reported insufficient available labor, with two farmers saying they had seen crops wasted because there was not enough labor available to harvest them in time. Adoption of farming machinery could have an immediate impact on profit margins, as the machinery could help reduce the number laborers needed.

Another shared challenge by the farmers was selling their products at a fair price. Farmers reported having to sell their products to a local broker, who would undermine the farmers by

forcing them to sell their products for a very low price. Then, the broker would transport the products to bigger cities where they were able to sell the products for much higher. This is a common issue in traditional farming, where the lack of access to transportation limits farmers' ability to sell their product directly to the end-user. In an effort to remedy this, policy makers should contribute towards improving farmers' access to markets. While farming machinery could help lower the cost of production, farmers would still be vulnerable to the controlled prices set by the brokers. An additional opportunity for technology to improve conditions would be to solve the issues related to market accessibility.

At the beginning of this study, farmers reported having minimal to no knowledge of modern farming machinery. They were reluctant to think machinery would improve their farming practices, with the following themes evident in their responses: (1) traditional farming has worked for generations and thus there is need to change; (2) their culture and environment are important, and machinery would interfere; (3) owning machinery would lead to too many complications such as maintenance, spare parts, and fuel; and (4) owning machinery would cause militia to perceive them as rich and as a result target them. This overall lack of experience and knowledge was also described by Bello [4], who reported that agricultural extension services (i.e., farming innovations that increase food production, such as machinery) reach only a limited number of farmers in Sudan. Despite this initial unease towards technology, all of the farmers were positively accepting of the machinery when offered for use during the 2020 farming season. After planting with the machinery, the farmers described the process as much cheaper (i.e., no laborers were hired), quicker (i.e., average planting time went from 4.1 weeks to 5.6 days), more efficient (i.e., utilize land space better), and safer (i.e., less physical exhaustion and no snake bites). All of the farmers described the machinery as very satisfactory. However, none of them expressed interest in long-

term adoption of the equipment; still referencing concerns over security, costs, and availability of fuel and spare parts.

Overall, at the beginning of this study, there was an initial resistance to using agricultural machinery due to lake of knowledge about farming machinery and also because of the nature of the traditional farming culture. But afterward, and at the end of this study, all of the farmers were pleased with their experience with the machinery in all farming processes. There is serious thinking about adopting farming machinery. In order to overcome the challenges posed by technology adoption and decrease rural poverty, education on modern equipment should be provided, and there is a need for the after-adoption facility, such as maintenance and fuel for equipment.

Chapter 5

ECONOMIC IMPACT OF AGRICULTURAL MACHINERY

5.1 Overview

The objective of this chapter is to quantify the profitability of farming practices in Sudan to identify feasible opportunities to integrate farming machinery; and ultimately move towards improving farming productivity and quality of life. Two farming approaches are evaluated, traditional farming without machinery and farming with machinery. The analysis used in this chapter focuses on the economic evaluation of traditional farming versus comparable mechanized farming to identify if and how the use of agricultural machinery could be adapted to satisfy the needs of farmers in developing economy countries. The following research questions are examined regarding farming in Sudan, Africa: *(1)* What are the major influences on farming costs and revenues; and *(2)* How does the use of machinery effect cost, revenue, net-profit, and return on investment.

5.2 Methods

The economic analysis of farming machinery was conducted based on data for the 2019 – 2021 farming seasons, based on cost and revenue data provided by the farmers. The farmers provided data in the local currency, the Sudanese pound (SDG) and these values were converted into USD for analysis. *Cost* was identified as the input in dollars for the season, such as labor, materials, and fuel from preparing soil to selling produce. *Revenue* was defined as the amount of money acquired for selling produce for the season. *Net-profit* was defined as the difference between cost and revenue, also in dollars. Each farmer was asked about their costs and revenues for each season, as well as how large their farm was in acres. To compare values between farms,

the costs, revenues, and net-profits were divided by farm size, to compare $/acre, since all the farms were slightly different sizes. Further, to evaluate the value and efficiency of machinery, *Return on Investment (ROI)* was also computed, which is the ratio of net-profit to cost, see equation 1. Where a higher ROI corresponds to a better investment. Further, any positive ROI value corresponds to a positive net-profit. For example, an ROI of 100% would indicate the revenue was double the cost (i.e., net-profit equaled cost), an ROI of 0% would indicate the revenue equaled the cost (i.e., net-profit of $0).

$$\text{ROI} = \frac{\text{Net profit}}{\text{Cost}} * 100\% \quad (1)$$

T-tests were used to evaluate differences in costs, revenues, and net-profits between the treatment and control groups for 2019 – the baseline farming year that all farmers in the study farmed without machinery. Analysis of Variance (ANOVAs) were used to test for the effects of farming year and machinery group on net-profits and return on investment for 2019 – 2021. Post hoc tests using Tukey Honest Significant Difference (HSD) were used to further evaluate ANOVA pairwise comparisons.

5.3 Similarities in Farm Characteristics

Recall, the farms included in this study for each region (i.e., north, east, west) farmed similar crops to the farms within their region. Each farm reported growing at least two different crops. The farms included to represent the north region farmed peanut, potato, and/or wheat; the farms in the east farmed carrot, cucumber, eggplant, green pepper, okra, potato, and/or tomato; the farms in the west farmed peanut, sesame, and/or watermelon seeds. All farmers conducted their planting and harvesting at similar times within the year. None of the farms used modern machinery to farm or sell their product, but rather used animal and human labor. None of the farmers in our study reported having a vehicle to transport their product, instead they would either transport their

goods via a cart pulled by an animal to sell direct to consumers in the local market or they would sell their product to a broker who would by everything at once at a reduced price and the broker would sell the product at larger markets.

In the first interview, the farmers were asked if they had to hire laborers over the previous three seasons (i.e., 2017, 2018, 2019) to assist in the farming process, and all of the farms in the control group and treatment group reported having to hire laborers in all of the past three farming seasons. The two groups also reported a similar number of family members working on their farm, where the control group had an average of 7.2 family members working on the farm (SD = 7.7, min = 5, max = 11) and the treatment group had an average of 6.8 family members working on the farm (SD = 3.6, min = 4, max = 14). The assignment of treatment and control group was randomly assigned to each farm, and the control group farms ended up being slightly smaller in size, where the control group had an average farm size of 39.7 acres (SD = 7.8, min = 25, max = 65) and the treatment group had an average farm size of 78.1 acres (SD = 25.1, min = 56, max = 120). However, subsequent analysis was conducted on $/acre for cost, revenue, and net-profit, hence it is not expected that this difference should significantly impact the analysis on the impact of machinery.

5.4 Factors Affecting Farming Net-Profits

Each of the 36 farmers were asked an open-ended question about what factors affected their farming net-profits. There were four factors identified by the farmers, see Figure 10. Notably, all 36 farmers mentioned exchange rate. Additionally, due to the high manual labor needed to farm without machinery, many traditional farmers hire extra laborers. Often, as reported by 25 of our 36 farmers (69.5%), they cannot find enough laborers to hire, or the laborers are too expensive. As a result, farmers reported not being able to harvest their entire crops on time, causing them to lose

part of their crops. Farming inputs include high-quality seeds, fertilizers, insecticides, pesticides, insect traps, and straw removers. Farmers (20 out of 36 or 55.5%) claimed they often have limited- to no-access to farming inputs or they are too expensive to buy. As a result, they switch to local alternatives that are less efficient and lead to less output [and profits]. For example, many of our farmers reported not being able to afford manufactured fertilizers, so they burn their land to create carbon that fertilizes their land, which is less efficient compared to manufactured fertilizers.

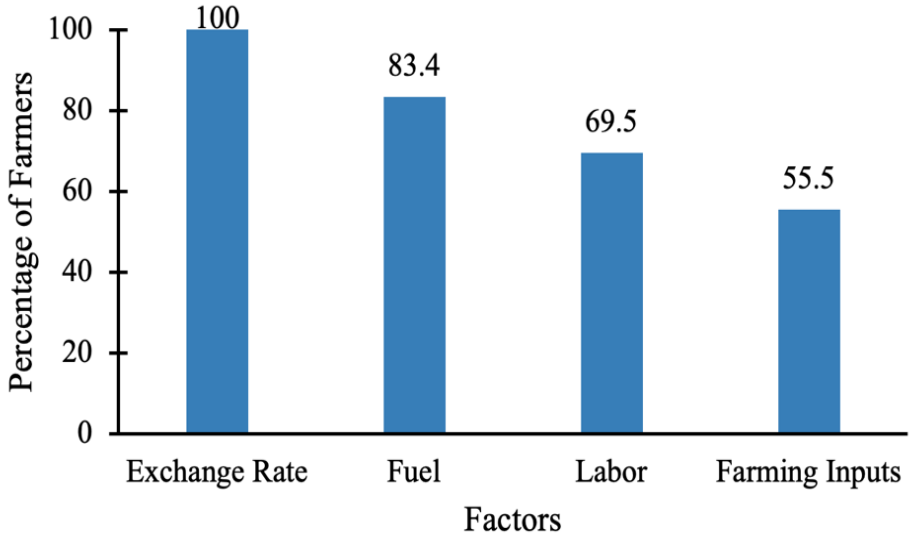


Figure 10. Factors that affect farming net-profits as identified by farmers

The exchange rate between the local currency (Sudanese Pound, SDG) and US Dollar (USD) has adversely affected farming practices. Farmers claim that the inconsistency in the value of the SDG often causes unpredictable fluctuations in the costs of inputs and the value of their outputs. In Sudan's case, there are two exchange rates: the official rate, which the Sudanese government and Sudanese banks use; and the black-market rate, which the actual economy is based on. Traditional farmers buy their farming needs and sell their products based on this black-market exchange rate because the people who sell the farming inputs and buy the products price based on the black-market rate. As such, the black-market exchange rate was used instead of the official-

market exchange rate because the farmers buy and sell through local merchants, who follow the black-market value of the SDG. These exchange rates are provided in Table 24.

Table 24. Exchange Rates for Black-Market and Official Markets Between USD and SDG

Farming Season	Black-Market *1 USD = ... SDG*	Official-Market *1 USD = ... SDG*
2019	68	55.25
2020	255.50	55.85
2021	447	447

There is often a large difference in the value of the SDG based on the official and black-market rates and between years. To demonstrate this, Figure 11 shows the net-profits for all 36 farmers based on the black-market and official exchange rates for each year, where the black-market vs. official values fluctuates from year to year and not consistently with each other. In all subsequent analysis, only the black-market exchange rate is considered.

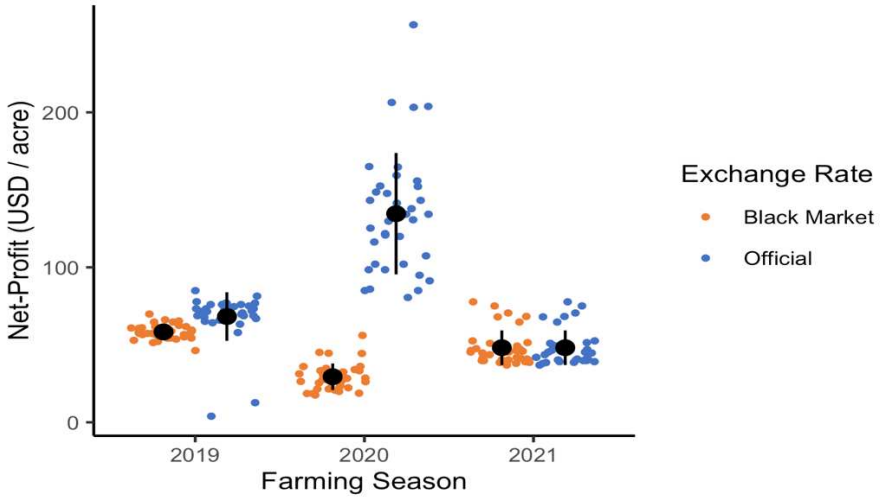


Figure 11. Net-profit per acre in USD based on exchange rates, mean +/- SD

5.5 Breakdown of Costs

Each farmer was asked to provide cost data for each farming season. They were asked to provide costs in terms of (1) amount spent on labor and (2) amount spent on farming inputs and transport. Farming inputs included seeds, fertilizers, insecticides, pesticides, insect traps, and straw removers. Transport included the cost of transporting the farming inputs from the local market back to the farms and transporting the final outputs to the market after harvesting. A summary of this is provided in Table 25. As a result of using the machinery, none of the farmers in the treatment group needed to hire labor, hence labor costs for this group were $0 in 2020 and 2021. Additionally, these estimates for cost do not include fuel to operate the machinery for the treatment group, since the fuel was provided as part of this study; more on fuel costs in the next section.

Table 25. Summary of Farming Costs ($/acre) by Category and Machinery Group

Farming Season	Machinery Group	Labor *Mean (SD)*	Inputs & Transport *Mean (SD)*
2019	Control	12.60 (0.79)	6.77 (0.94)
	Treatment	14.83 (0.72)	4.04 (1.01)
2020	Control	7.66 (0.47)	12.41 (0.80)
	Treatment	0 (0)	13.81 (0.97)
2021	Control	9.92 (0.38)	17.22 (0.86)
	Treatment	0 (0)	18.75 (0.604)

5.6 Cost of Fuel to Farm with Machinery

As mentioned previously, the fuel was provided to the farmers as part of the study. Due to limitations in communication between the research team, farmers, and local Sudanese person hired to assist with data collection, only fuel usage data was reliably recorded in the final farming year (2021) for three of the six farms using machinery. Table 26 shows the total cost of fuel for the entire 2021 farming season (from preparing the soil through harvesting) for these farms. The average fuel cost using machinery for the entire season was $3.65 per acre (SD $0.07). The small standard deviation suggests that this small sample size of fuel cost should not be a hindrance. Since participants did not pay for the fuel to power the tractors, their reported values of farming costs did not include fuel. Hence, we added the price of fuel ($/acre) to their reported costs ($/acre) in subsequent analysis to get a realistic estimate of farming with machinery costs.

Table 26. Fuel Costs for Entire 2021 Farming Season

Farm Size	**Fuel Cost for Season**	**Cost Per Acre**	**Summary**
Acres	*USD*	*USD / acre*	*Mean (SD)*
39	145.00	3.72	
35	128.00	3.66	3.65 (0.07)
56	200.00	3.57	

5.7 Cost, Revenues, and Net-Profits Between Groups

The 30 participants in the control group provided costs and revenues over the last three farming seasons (2019-2021), which were used to compute net-profit, which are summarized in Table 27. The cost of farming increased as the black-market exchange rate increased. However, the revenue did not necessarily follow similarly, causing fluctuations in net-profit.

Table 27. Summary of Financial Data ($/acre) for Control Group

Farming Season	Exchange Rate *1 USD = ... SDG*	Cost *mean (SD)*	Revenue *mean (SD)*	Net-Profit *mean (SD)*
2019	68	19.37 (1.63)	77.84 (4.61)	58.47 (4.94)
2020	255.5	20.07 (1.01)	46.73 (5.44)	26.66 (5.48)
2021	447	27.13 (0.86)	70.77 (4.19)	43.64 (4.46)

The individual values provided by each farmer in the control group used to compute these summaries above are provided as follows: 2019 costs (Table 28), 2019 revenue (Table 29), 2019 net-profits (Table 30), 2020 costs (Table 31), 2020 revenue (Table 32), 2020 net-profits (Table 33), 2021 costs (Table 34), 2021 revenue (Table 35), and 2021 net-profits (Table 36).

Table 28. Control Group 2019 Farming Season Costs

Farmer ID	Cost per Acre *SDG*	USD Official *1USD = 55.25 SDG*	USD Black Market *1USD = 68 SDG*
1	1360	24.62	20.00
2	1100	19.91	16.18
3	1250	22.62	18.38
4	1300	23.53	19.12
5	1350	24.43	19.85
6	1400	25.34	20.59
7	1300	23.53	19.12
8	1200	21.72	17.65
9	1250	22.62	18.38
10	1000	18.10	14.71
11	1500	27.15	22.06
12	1400	25.34	20.59
13	1300	23.53	19.12
14	1350	24.43	19.85
15	1200	21.72	17.65
16	1450	26.24	21.32
17	1305	23.62	19.19
18	1250	22.62	18.38
19	1375	24.89	20.22
20	1400	25.34	20.59
21	1450	26.24	21.32
22	1200	21.72	17.65
23	1500	27.15	22.06
24	1400	25.34	20.59
25	1350	24.43	19.85
26	1250	22.62	18.38
27	1350	24.43	19.85
28	1275	23.08	18.75
29	1400	25.34	20.59
30	1300	23.53	19.12

Table 29. Control Group 2019 Farming Season Revenue

Farmer ID	Revenue per Acre *SDG*	USD Official *1 USD = 55.25 SDG*	USD Black Market *1 USD = 68 SDG*
1	5500	99.55	80.88
2	5000	90.50	73.53
3	4800	86.88	70.59
4	5300	95.93	77.94
5	5800	104.98	85.29
6	5600	101.36	82.35
7	5500	99.55	80.88
8	5200	94.12	76.47
9	5000	90.50	73.53
10	5400	97.74	79.41
11	5000	90.50	73.53
12	5250	95.02	77.21
13	5700	103.17	83.82
14	4500	81.45	66.18
15	5200	94.12	76.47
16	5400	97.74	79.41
17	5000	90.50	73.53
18	6000	108.60	88.24
19	5300	95.93	77.94
20	5500	99.55	80.88
21	5100	92.31	75.00
22	5700	103.17	83.82
23	5400	97.74	79.41
24	5000	90.50	73.53
25	5200	94.12	76.47
26	5300	95.93	77.94
27	5500	99.55	80.88
28	5400	97.74	79.41
29	5250	95.02	77.21
30	5000	90.50	73.53

Table 30. Control Group 2019 Farming Season Net-Profits

Farmer ID	Net-Profit *SDG*	USD Official *1 USD = 55.25 SDG*	USD Black Market *1 USD = 68 SDG*
1	4140	74.93	60.88
2	3900	70.59	57.35
3	3550	64.25	52.21
4	4000	72.40	58.82
5	4450	80.54	65.44
6	4200	76.02	61.76
7	4200	76.02	61.76
8	4000	72.40	58.82
9	3750	67.87	55.15
10	4400	79.64	64.71
11	3500	63.35	51.47
12	3850	69.68	56.62
13	4400	79.64	64.71
14	3150	57.01	46.32
15	4000	72.40	58.82
16	3950	71.49	58.09
17	3695	66.88	54.34
18	4750	85.97	69.85
19	3925	71.04	57.72
20	4100	74.21	60.29
21	3650	66.06	53.68
22	4500	81.45	66.18
23	3900	70.59	57.35
24	3600	65.16	52.94
25	3850	69.68	56.62
26	4050	73.30	59.56
27	4150	75.11	61.03
28	4125	74.66	60.66
29	3850	69.68	56.62
30	3700	66.97	54.41

Table 31. Control Group 2020 Farming Season Costs

Farmer ID	Cost per Acre *SDG*	USD Official *1 USD = 55.85 SDG*	USD Black Market *1 USD = 255.5 SDG*
1	5000	89.53	19.57
2	4500	80.57	17.61
3	4800	85.94	18.79
4	5250	94.00	20.55
5	5200	93.11	20.35
6	5500	98.48	21.53
7	5300	94.90	20.74
8	5100	91.32	19.96
9	5200	93.11	20.35
10	5200	93.11	20.35
11	5500	98.48	21.53
12	4800	85.94	18.79
13	5000	89.53	19.57
14	4750	85.05	18.59
15	5500	98.48	21.53
16	5250	94.00	20.55
17	5300	94.90	20.74
18	5000	89.53	19.57
19	5500	98.48	21.53
20	5300	94.90	20.74
21	5200	93.11	20.35
22	5000	89.53	19.57
23	4800	85.94	18.79
24	5000	89.53	19.57
25	5250	94.00	20.55
26	5000	89.53	19.57
27	5500	98.48	21.53
28	5100	91.32	19.96
29	5250	94.00	20.55
30	4800	85.94	18.79

Table 32. Control Group 2020 Farming Season Revenue

Farmer ID	Revenue per Acre *SDG*	USD Official *1 USD = 55.85 SDG*	USD Black Market *1 USD = 255.5 SDG*
1	12000	214.86	46.97
2	10000	179.05	39.14
3	14000	250.67	54.79
4	12000	214.86	46.97
5	12000	214.86	46.97
6	10000	179.05	39.14
7	11000	196.96	43.05
8	13000	232.77	50.88
9	12500	223.81	48.92
10	10000	179.05	39.14
11	11000	196.96	43.05
12	11500	205.91	45.01
13	12500	223.81	48.92
14	12000	214.86	46.97
15	14000	250.67	54.79
16	13500	241.72	52.84
17	11000	196.96	43.05
18	10100	180.84	39.53
19	12000	214.86	46.97
20	13000	232.77	50.88
21	13500	241.72	52.84
22	12500	223.81	48.92
23	13500	241.72	52.84
24	11000	196.96	43.05
25	10000	179.05	39.14
26	13000	232.77	50.88
27	13500	241.72	52.84
28	14000	250.67	54.79
29	10000	179.05	39.14
30	10100	180.84	39.53

Table 33. Control Group 2020 Farming Season Net-Profit

Farmer ID	Net-Profit *SDG*	USD Official *1 USD = 55.85 SDG*	USD Black Market *1 USD = 255.5 SDG*
1	7000	125.34	27.40
2	5500	98.48	21.53
3	9200	164.73	36.01
4	6750	120.86	26.42
5	6800	121.75	26.61
6	4500	80.57	17.61
7	5700	102.06	22.31
8	7900	141.45	30.92
9	7300	130.71	28.57
10	4800	85.94	18.79
11	5500	98.48	21.53
12	6700	119.96	26.22
13	7500	134.29	29.35
14	7250	129.81	28.38
15	8500	152.19	33.27
16	8250	147.72	32.29
17	5700	102.06	22.31
18	5100	91.32	19.96
19	6500	116.38	25.44
20	7700	137.87	30.14
21	8300	148.61	32.49
22	7500	134.29	29.35
23	8700	155.77	34.05
24	6000	107.43	23.48
25	4750	85.05	18.59
26	8000	143.24	31.31
27	8000	143.24	31.31
28	8900	159.36	34.83
29	4750	85.05	18.59
30	5300	94.90	20.74

Table 34. Control Group 2021 Farming Season Costs

Farmer ID	Cost per Acre *SDG*	USD Official *1 USD = 447 SDG*	USD Black Market *1 USD = 447 SDG*
1	12000	26.85	26.85
2	11500	25.73	25.73
3	11750	26.29	26.29
4	12500	27.96	27.96
5	12500	27.96	27.96
6	12200	27.29	27.29
7	11500	25.73	25.73
8	11250	25.17	25.17
9	12250	27.40	27.40
10	12000	26.85	26.85
11	12750	28.52	28.52
12	12500	27.96	27.96
13	12200	27.29	27.29
14	12500	27.96	27.96
15	12000	26.85	26.85
16	12250	27.40	27.40
17	11500	25.73	25.73
18	12000	26.85	26.85
19	12750	28.52	28.52
20	12500	27.96	27.96
21	11750	26.29	26.29
22	12000	26.85	26.85
23	12250	27.40	27.40
24	12200	27.29	27.29
25	12500	27.96	27.96
26	12300	27.52	27.52
27	12000	26.85	26.85
28	11750	26.29	26.29
29	12200	27.29	27.29
30	12500	27.96	27.96

Table 35. Control Group 2021 Farming Season Revenue

Farmer ID	Revenue per Acre *SDG*	USD Official *1 USD = 447 SDG*	USD Black Market *1 USD = 447 SDG*
1	30000	67.11	67.11
2	32000	71.59	71.59
3	33000	73.83	73.83
4	31000	69.35	69.35
5	29000	64.88	64.88
6	30000	67.11	67.11
7	35000	78.30	78.30
8	32000	71.59	71.59
9	32500	72.71	72.71
10	30000	67.11	67.11
11	31000	69.35	69.35
12	32000	71.59	71.59
13	35000	78.30	78.30
14	29500	66.00	66.00
15	32000	71.59	71.59
16	33000	73.83	73.83
17	32500	72.71	72.71
18	34000	76.06	76.06
19	35000	78.30	78.30
20	30000	67.11	67.11
21	29000	64.88	64.88
22	30000	67.11	67.11
23	31000	69.35	69.35
24	30000	67.11	67.11
25	30000	67.11	67.11
26	33000	73.83	73.83
27	35000	78.30	78.30
28	32000	71.59	71.59
29	29500	66.00	66.00
30	31000	69.35	69.35

Table 36. Control Group 2021 Farming Season Net-Profits

Farmer ID	Net-Profit *SDG*	USD Official *1 USD = 447 SDG*	USD Black Market *1 USD = 447 SDG*
1	18000	40.27	40.27
2	20500	45.86	45.86
3	21250	47.54	47.54
4	18500	41.39	41.39
5	16500	36.91	36.91
6	17800	39.82	39.82
7	23500	52.57	52.57
8	20750	46.42	46.42
9	20250	45.30	45.30
10	18000	40.27	40.27
11	18250	40.83	40.83
12	19500	43.62	43.62
13	22800	51.01	51.01
14	17000	38.03	38.03
15	20000	44.74	44.74
16	20750	46.42	46.42
17	21000	46.98	46.98
18	22000	49.22	49.22
19	22250	49.78	49.78
20	17500	39.15	39.15
21	17250	38.59	38.59
22	18000	40.27	40.27
23	18750	41.95	41.95
24	17800	39.82	39.82
25	17500	39.15	39.15
26	20700	46.31	46.31
27	23000	51.45	51.45
28	20250	45.30	45.30
29	17300	38.70	38.70
30	18500	41.39	41.39

The six farmers in the treatment group used the machinery for two farming seasons (2020 and 2021), while 2019 provided data for these farmers not using machinery (i.e., comparable to the control group), their financial values are summarized in Table 37.

Table 37. Summary of Financial Data ($/acre) for Treatment Group

Farming Season	Machinery	Exchange Rate *1 USD = ... SDG*	Cost *mean (SD)*	Revenue *mean (SD)*	Net-Profit *mean (SD)*
2019	no	68	18.87 (1.00)	76.59 (2.81)	57.72 (2.97)
2020	yes	255.5	17.46 (0.97)	60.73 (7.84)	43.27 (8.01)
2021	yes	477	22.40 (0.60)	93.14 (4.42)	70.74 (4.86)

The individual values provided by each treatment group farmer used to compute the above summaries are provided as follows: 2019 costs (Table 38), 2019 revenue (Table 39), 2019 net-profits (Table 40), 2020 costs (Table 41), 2020 revenue (Table 42), 2020 net-profits (Table 43), 2021 costs (Table 44), 2021 revenue (Table 45), and 2021 net-profits (Table 46).

Table 38. Treatment Group 2019 Farming Season Costs

Farmer ID	Cost per Acre *SDG*	USD Official *1 USD = 55.25 SDG*	USD Black Market *1 USD = 68 SDG*
1	1300	23.53	19.12
2	1200	21.72	17.65
3	1250	22.62	18.38
4	1400	25.34	20.59
5	1300	23.53	19.12
6	1250	22.62	18.38

Table 39. Treatment Group 2019 Farming Season Revenue

Farmer ID	Return per Acre *SDG*	USD Official *1 USD = 55.25 SDG*	USD Black Market *1 USD = 68 SDG*
1	5000	90.50	73.53
2	5250	95.02	77.21
3	5000	90.50	73.53
4	5300	95.93	77.94
5	5200	94.12	76.47
6	5500	99.55	80.88

Table 40. Treatment Group 2019 Farming Season Net-Profits

Farmer ID	Net-Profit *SDG*	USD Official *1 USD = 55.25 SDG*	USD Black Market *1 USD = 68 SDG*
1	3700	66.97	54.41
2	4050	73.30	59.56
3	3750	67.87	55.15
4	3900	70.59	57.35
5	3900	70.59	57.35
6	4250	76.92	62.50

Table 41. Treatment Group 2020 Farming Season Costs

Farmer ID	Cost per Acre *SDG*	USD Official *1 USD = 55.85 SDG*	USD Black Market *1 USD = 255.5 SDG*
1	3500	66.32	17.35
2	3150	60.05	15.98
3	3360	63.81	16.80
4	3675	69.45	18.03
5	3640	68.82	17.90
6	3850	72.58	18.72

Table 42. Treatment Group 2020 Farming Season Revenue

Farmer ID	Revenue per Acre *SDG*	USD Official *1 USD = 55.85 SDG*	USD Black Market *1 USD = 255.5SDG*
1	15960	285.77	62.47
2	13300	238.14	52.05
3	18620	333.39	72.88
4	15960	285.77	62.47
5	15960	285.77	62.47
6	13300	238.14	52.05

Table 43. Treatment Group 2020 Farming Season Net-Profits

Farmer ID	Net-Profit *SDG*	USD Official *1 USD = 55.85 SDG*	USD Black Market *1 USD = 255.5 SDG*
1	12460	223.10	48.77
2	10150	181.74	39.73
3	15260	273.23	59.73
4	12285	219.96	48.08
5	12320	220.59	48.22
6	9450	169.20	36.99

Table 44. Treatment Group 2021 Farming Season Costs

Farmer ID	Cost per Acre *SDG*	USD Official *1 USD = 447 SDG*	USD Black Market *1 USD = 447 SDG*
1	8340	22.31	22.31
2	7995	21.54	21.54
3	8165	21.92	21.92
4	8685	23.08	23.08
5	8650	23.00	23.00
6	8450	22.55	22.55

Table 45. Treatment Group 2021 Farming Season Revenue

Farmer ID	Revenue per Acre *SDG*	USD Official *1 USD = 447 SDG*	USD Black Market *1 USD = 447 SDG*
1	40500	90.60	90.60
2	43200	96.64	96.64
3	44550	99.66	99.66
4	41850	93.62	93.62
5	39200	87.70	87.70
6	40500	90.60	90.60

Table 46. Treatment Group 2021 Farming Season Net-Profits

Farmer ID	Net-Profit *SDG*	USD Official *1 USD = 447 SDG*	USD Black Market *1 USD = 447 SDG*
1	32160	71.95	71.95
2	35205	78.76	78.76
3	36385	81.40	81.40
4	33165	74.19	74.19
5	30550	68.34	68.34
6	32050	71.70	71.70

There were no significant differences between the 2019 values for the farmers in the control vs. treatment groups for costs: $t(11.12) = 0.98$, $p = .347$, $\mu_{treatment} = 18.87$ vs. $\mu_{control} = 19.37$; revenues: $t(11.30) = 0.88$, $p = .398$, $\mu_{treatment} = 76.59$ vs. $\mu_{control} = 77.84$; and net-profits: $t(11.45) = 0.50$, $p = .628$, $\mu_{treatment} = 57.72$ vs. $\mu_{control} = 58.47$. As such, this validates that the treatment and control groups have similar baseline values and would likely otherwise experience similar farming seasons in 2020 and 2021 if it was not for the farming machinery provided in this study.

5.8 Net-Profit Benefit of Machinery

A side-by-side comparison is provided in Figure 12 of the net-profits in 2019, 2020, and 2021 for the control group and the treatment group farmers. The net-profits are very similar in 2019, when both groups were farming without machinery, but in subsequent years the treatment group consistently has higher net-profit than the control group. The value of the Sudanese pound was the highest in 2019 of the three years, hence why the net-profit appears high in the first year. However, comparison between the groups within each year is indicative of the effect of machinery.

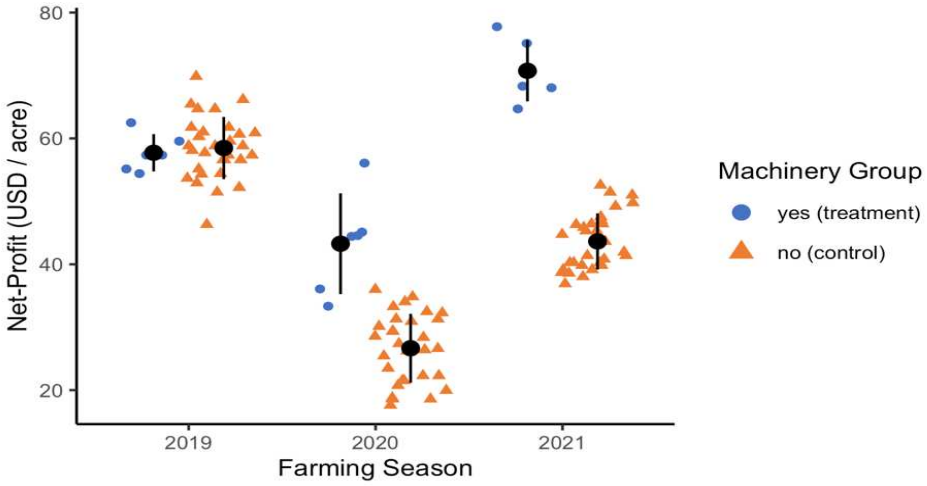


Figure 12. Comparison of net-profit ($/acre) with and without farming machinery, mean +/- SD.

An ANOVA was performed to compare effects of the interaction of farming season and machinery group on the net-profits, in USD per acre. There was a significant effect of year [$F(2, 102) = 289.86$, $p < .001$], machinery group [$F(1, 102) = 119.11$, $p < .001$] and year by machinery group [$F(2, 102) = 38.32$, $p < .001$] on net-profit. A Tukey HSD post hoc test indicated a statistically significant difference ($p < .01$) between all pairwise comparisons of group by year except for two: *(1)* 2019 control vs. 2019 treatment ($p = .999$), which indicates similarity when

both groups were farming without machinery; and *(2)* 2020 treatment vs. 2021 control, which speaks to the volatility in the value of the SDG. More specifically, the use of machinery was associated with a 62.30% increase in net-profit for the 2020 season ($26.66/acre vs. $43.27/acre) and a 62.01% increase in net-profit for the 2021 season ($43.64/acre vs $70.74/acre).

5.9 Return on Investment (ROI) Between Groups

In the case of this dissertation, to calculate the financial benefits of using or adopting farming machinery and evaluate the value and efficiency of machinery, rate of investment or return on investment (ROI) method is used to do this evaluation. ROI was used to provide an indication of the relative usefulness of the farming practice. However, this analysis does not include the cost of the machinery since it was provided to the farmers. Hence, this ROI analysis is representative of the relative impact of mechanized farming rather than specific to the value of the machinery. Moreover, this would represent the case where the machinery is paid off, borrowed, shared amongst farms, and/or provided by policy initiatives.

The ROI data for each farmer in the control group for the 2019, 2020, and 2021 farming season is in the Table 47 and the data from the treatment group for the 2019, 2020, and 2021 farming season is in the Table 48. Additionally, Figure 13 compares the ROI for the control group over these farming seasons and Figure 14 compares the ROI for the treatment group over these farming seasons.

Table 47. ROI Data for Each Control Group Farmer by Year

Farmer ID	2019 Season ROI *(%)*	2020 Season ROI *(%)*	2021 Season ROI *(%)*
1	304.41	140.00	150.00
2	354.55	122.22	178.26
3	284.00	191.67	180.85
4	307.69	128.57	148.00
5	329.63	130.77	132.00
6	300.00	81.82	145.90
7	323.08	107.55	204.35
8	333.33	154.90	184.44
9	300.00	140.38	165.31
10	440.00	92.31	150.00
11	233.33	100.00	143.14
12	275.00	139.58	156.00
13	338.46	150.00	186.89
14	233.33	152.63	136.00
15	333.33	154.55	166.67
16	272.41	157.14	169.39
17	283.14	107.55	182.61
18	380.00	102.00	183.33
19	285.45	118.18	174.51
20	292.86	145.28	140.00
21	251.72	159.62	146.81
22	375.00	150.00	150.00
23	260.00	181.25	153.06
24	257.14	120.00	145.90
25	285.19	90.48	140.00
26	324.00	160.00	168.29
27	307.41	145.45	191.67
28	323.53	174.51	172.34
29	275.00	90.48	141.80
30	284.62	110.42	148.00

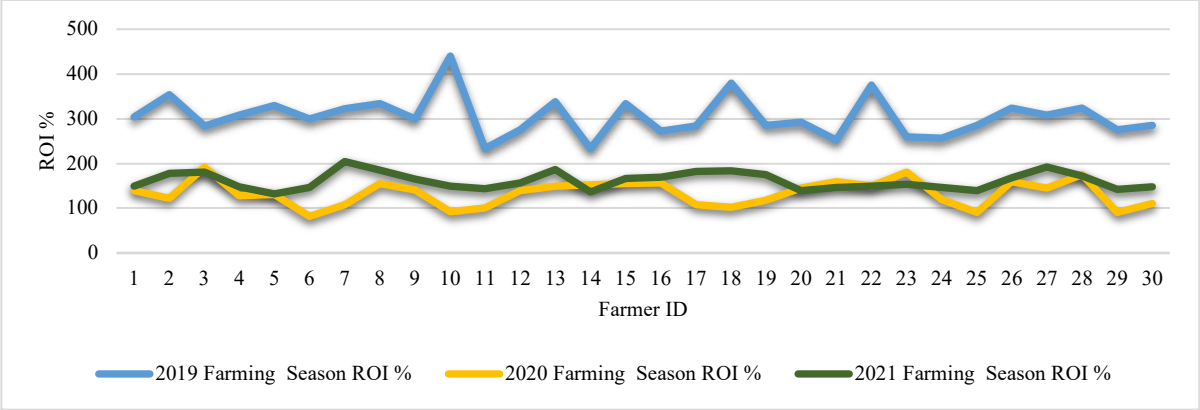


Figure 13. ROI comparison for control group farmers over the 2019, 2020, and 2021 farming seasons

Table 48. ROI Data for Each Treatment Group Farmer by Year

Farmer ID	2019 Season ROI *(%)*	2020 Season ROI *(%)*	2021 Season ROI *(%)*
1	284.62	260.06	306.16
2	337.50	225.77	348.76
3	300.00	333.77	354.75
4	278.57	246.39	305.66
5	300.00	249.04	281.27
6	340.00	178.09	301.72

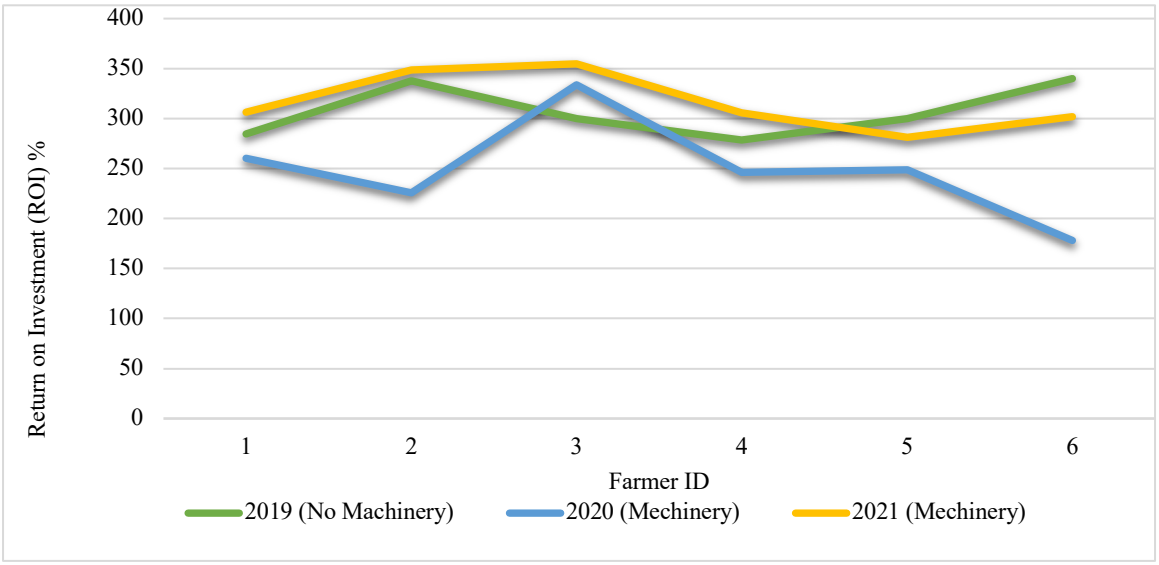


Figure 14. ROI comparison for treatment group farmers over the 2019, 2020, and 2021 farming seasons

Table 49 summarizes the ROI across farming seasons for each group. As shown, the ROI for farming is largely affected by the country's economy, which is represented by the exchange rate. When the exchange rate was low in 2019 (1 USD = 68 SDG), the average ROI was 304.9% (without) and 306.8% (with). However, when the exchange rate increased, indicating less value of the SDG, the average ROI decreased to 133.3% (control group) and 248.9% (treatment group) in 2020 (1 USD = 255.5 SDG) and 161.2% (control group) and 316.4% (treatment group) in 2021 (1 USD = 447 SDG).

Table 49. Summary of ROI by Machinery Group

Summary Statistic	2019 Farming Season (%)		2020 Farming Season (%)		2021 Farming Season (%)	
	Control	Treatment	Control	Treatment	Control	Treatment
Machinery	No	No	No	Yes	No	Yes
Mean	304.92	306.78	133.31	248.90	161.18	316.41
St. Dev.	44.79	26.18	28.86	50.77	19.18	28.94
Median	300.00	300.00	139.79	247.76	154.53	305.93
Min	233.33	278.57	81.82	178.13	132.00	281.29
Max	440.00	340.00	191.67	333.83	204.35	354.78
95% Conf.	16.73	27.48	10.78	40.62	7.17	23.16

Moreover, the treatment group's ROI was only 0.61% greater than the control group for 2019, which is expected since both groups were farming without machinery in 2019. However, in 2020, the treatment group's ROI was 86.7% greater than the control group and 96.3% greater in 2021. Despite the fluctuations between years due to the value of the SDG, the treatment group yielded much higher ROIs as compared to the control group for the same year.

5.10 Return on Investment (ROI) Benefit of Machinery

Similar to the net-profit analysis, a comparison of the 2019, 2020 and 2021 ROIs for the treatment and control group farmers is provided in Figure 15. As like before, the relatively higher values are expected in 2019 due to the exchange rate. However, within each year there is significant differences in between the groups.

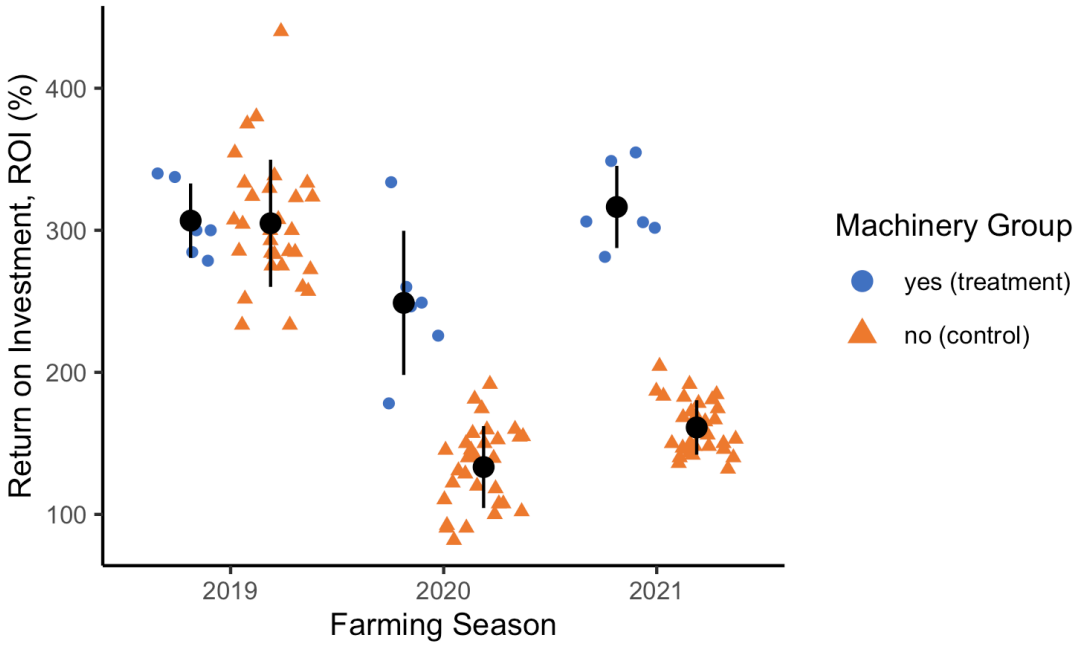


Figure 15. Comparison of ROI with and without farming machinery, mean +/- SD

An ANOVA was also used to evaluate the statistical difference in ROI based on year and machinery group. The results showed a significant effect of year [$F(2, 102) = 207.39$, $p < .001$], machinery group [$F(1, 102) = 111.38$, $p < .001$] and year by machinery group [$F(2, 102) = 28.48$, $p < .001$] on ROI. Further, the results of the post hoc Tukey HSD test indicated no significant difference ($p > .05$) between 2019 control vs. 2019 treatment, and significant difference ($p < .01$) in ROI between 2020 control vs. 2020 treatment and 2021 control vs. 2021 treatment.

5.11 Chapter Discussion and Summary

This chapter examined the economic feasibility and profitability of using agricultural machinery in Sudan. The use of farming machinery has been linked to increased output while decreasing strenuous labor; however, technology adoption requires user acceptance and often traditional farmers are resistant to new, unknown technology.

A shared challenge identified by all the farmers was the variability in the value of the Sudanese local currency (Sudanese Pound, SDG). This was demonstrated by converting the Sudanese Pound to the US Dollar (USD), which is a more stable and more widely relatable to the average reader. However, in the case of Sudan, there are two exchange rates, the official rate followed by the government and banks, and the black-market rate that the local [farming] economy is based on. The black-market value often deviates significantly from the official-market value, as well as from year to year. As a result, the costs, especially of farming inputs, and revenues, particularly value paid for product, leads to inconsistency for the farmers. This uncontrolled exchange rate negatively effects the country's general economy, limiting the country's ability to support its farmers and other economic sectors. Moreover, tractors are likely imported and paid for at official exchange rates, so it is important to consider how farmers might perceive these different values of the SDG.

Labor shortages and high costs were also identified by most of the farmers as having a significantly negative impact on their farming net-profits. However, farmers using the machinery required significantly fewer human workers throughout the process, which was one of the major causes for the difference between the farming groups' net-profits and ROIs. Others have reported similar findings, where the use of farming technologies reduce drudgery of farmers, especially with women and children (Mehta et al., 2012; Gregg et al., 2020). Even with the cost of fuel included in the cost of farming with machinery, which we found to add, on average, an extra $3.65/acre for the entire farming season, mechanized farming provided an advantage.

Financial data for the same three farming seasons, 2019, 2020, and 2021, were gathered for all 36 farms in the study. All the farmers, regardless of machinery group assignment, used traditional farming (i.e., no machinery) in the 2019 season. Since there was no statistically

significant difference between the farming groups' costs, revenues, net-profits, and ROIs for 2019, it is fair to assume that the treatment group would have experienced similar financial values to the control group if they had not had access to the machinery. Hence, the observed differences in 2020 and 2021 that we observed in our study between the two groups is most likely due to mechanized farming practices.

The analysis on the control group for the 2019 – 2021 farming seasons highlights how farming costs and revenues are largely dependent on the economic measure (i.e., black-market exchange rate); as evident by the fluctuations in costs and revenues despite the consistent farming practices for this group. The use of farming machinery helped lower costs and increase revenues enough to help overcome much of these deficits. In both 2020 and 2021, the treatment group reported significantly higher net-profits and returns on investment than the control group for each respective year. The net-profit per acre increased by 62.30% in 2020 ($43.27/acre vs. $26.66/acre) and by 62.01% in 2021 ($70.74/acre vs. $43.64/acre) for the farmers with machinery compared to those without machinery. The ROI increased by 86.7% in 2020 (248.9% vs. 133.3%) and by 96.3% in 2021 (316.4% vs. 161.2%) for the farmers with machinery compared to those without machinery. Follow-up interviews with the farmers indicated that the machinery helped increase these values by: (1) decreasing space between plants, resulting in increased farmed area; (2) enabling farmers to harvest their entire crop on time; and (3) increasing soil aeration, leading to better crops.

The financial gains per acre identified in this chapter can be used in future work to inform tractor design requirements. Previous literature has advocated for scale-appropriate and affordable machinery for smallholder farmers (Mottaleb et al., 2016; Ekawati et al., 2021). For example, Baudron et al (2015) suggested small, low horsepower, two-wheel tractors. Similarly, Paudel et al

(2019) proposed small, 5-7 horsepower two-wheel tractors, but found on average, farmers' willingness to pay was 31% less than the price of such a tractor. This chapter builds on this previous research by quantifying the monetary improvements realized through farm mechanization, which can be used in modeling purchase plans, outreach to farmers, and setting cost thresholds for equipment.

Most of the farmers in this study were hesitant to adopt new farming practices and technology, fearing that new practices would bring new headaches to the farming process. So, the farmers in the study were provided all machinery, fuel, and training at no cost to them. While we were able to estimate the cost of fuel based on three farms, this data was limited. Another limitation is that there are likely to be other costs, such as accessing fuel and servicing the equipment. Hence, future decisions based on the increased net-profits calculated in this study due to mechanized farming should factor in additional costs that might need to be incurred by the farmers for operating and maintaining the machinery, should that fall on the individual farmers. Additionally, future work could use a similar framework to analyze ROI for various tractor designs, by factoring in the cost of various tractors.

5.12 Chapter Conclusions

Overall, this chapter sought to quantify the financial benefits of utilizing farming machinery for rural, traditional farmers. More broadly, to identify a means for developing economy countries, such as Sudan, to successfully integrate agricultural machinery into their farming practices, to achieve pro-poor growth. All the farmers in this study had similar costs, revenues, and net-profits when farming without machinery. After using machinery to farm, the net-profits were significantly higher than their control counterparts for each comparable year ($16.61 per acre more in 2020 and $27.10 per acre more in 2021). The average farm in this study

was 44.86 acres, hence could equate to, on average, $745.14 to $1215.74 more per year for an individual farm. These differences identified in net-profits between farming with and without machinery provides a means to develop purchasing and borrowing models for farms to adopt machinery through economical and quantifiable solutions.

Chapter 6

NEEDS AND REQUIREMENTS ANALYSIS ON TRACTOR DESIGN

6.1 Overview

The overall objective of this chapter is to utilize leverage a human-systems integration approach to develop and incorporate farming machinery that satisfies users' needs and expectations. This is achieved by addressing three research objectives: *(1)* identify the needs and perceptions of traditional farmers in Sudan regarding tractor machinery; *(2)* identify general tractor design requirements to meet these needs; and *(3)* develop payback models for tractor adoption by these farmers.

6.2 Methods

The responses from all 36 farmers were aggregated to identify needs and expectations. However, these responses were also compared between farmers with machinery experience (treatment group) and farmers without machinery experience (control group). The raw responses provided by the farmers were grouped into similar themes. For example, several farmers stated they preferred owning a tractor over renting a tractor because owning allowed them full control over machinery, or no restrictions of use, or the ability to do anything with it, where all these responses described "full control over machinery" and hence were grouped together.

The statistical methods used in this chapter include t-tests comparing farm size responses and chi-square (or Fisher Exact when contingency tables are small) tests to compare the experience and no experience with machinery groups. Lastly, two payback models are presented for viable farming machinery that satisfies needs.

6.3 Farm Sizes

Recall, there were 36 farms in this study, and the average farm size was 44.39 acres (SD 19.33 acres). Each participant was asked what the minimum farm size would be for them to consider using tractor machinery, see Table 50. There was no significant difference in the minimum farm size needed to adopt a tractor between the group with no machinery experience (Mean = 44.83, SD = 11.19) and the group with machinery experience (Mean = 48.33, SD = 6.83), $t(11.253) = 1.302$, $p = .219$.

Table 50. Descriptive Statistics of Farm Sizes

Descriptive Statistic	Current Farm Size	Minimum Land Size for Using Tractor		
		Combined	*No Experience*	*Experience*
Mean	44.39	44.58	44.83	48.33
SD	19.32	10.65	11.19	6.83
Median	39.50	50.00	50.00	47.50
Mode	35.00	50.00	50.00	45.00
Min	20.00	0.00	0.00	40.00
Max	120.0	60.00	60.00	60.00
CI (95.0%)	6.31	3.48	4.00	5.47

6.4 Owning Over Renting a Tractor

Farmers were asked about their preference between owning or renting a tractor, and 88.9% ($N_{no\ experience} = 27$, $N_{experience} = 5$) reported that they rather own the tractor over renting one. They were also asked [open-ended] to explain their preference, there were three primary reasons for choosing to buy over rent, which are also shown in Figure 16:

1. *No Restrictions* (N = 31: $P_{no\ experience} = 83.3\%$, $P_{experience} = 100\%$). All of the participants except for one that preferred owning over renting referenced the flexibility of ownership over renting. They described that having ownership meant full control over how/when they used, maintained, sold, rented/lent to others the machinery. It also meant that they were not in debt to someone, and that if something happened to the equipment, there wouldn't be any outside consequences.
2. *Asset for Farmer* (N = 5: $P_{no\ experience} = 13.3\%$, $P_{experience} = 16.7\%$). Several participants explained that owning the tractor would make it an asset to them and they could sell it at any time if needed. Whereas with renting, they would be locked into a lease agreement.
3. *More Economical* (N = 2: $P_{no\ experience} = 3.3\%$, $P_{experience} = 16.7\%$). Two of the participants believed that owning machinery was a better deal, and that renting usually had a surcharge built into the fee.

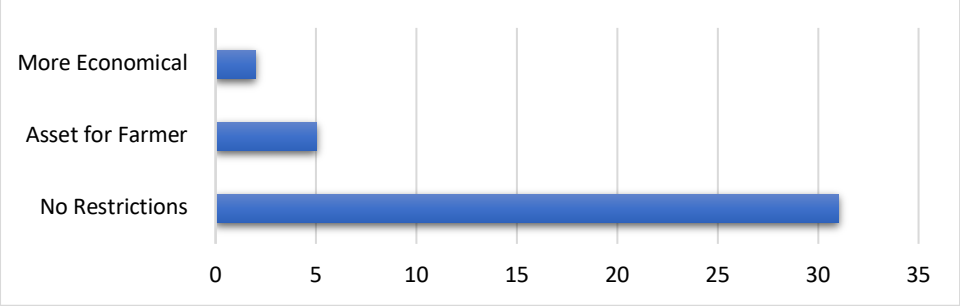


Figure 16. Reasons for owning farming machinery

Alternatively, all four participants that preferred renting explained that they preferred not to be liable for repairs and not be locked into a potentially outdated tractor, but rather have the opportunity to upgrade.

6.5 Tractor Design Preferences

Each farmer was asked an open-ended question to explain what features were most important for a tractor to include in order for it to be useful to them. Their responses were categorized into three concepts, which is also illustrated in Figure 17:

1. *Fuel Consumption* (N = 30: $P_{\text{no experience}} = 76.7\%$, $P_{\text{experience}} = 100\%$). Most farmers indicated that it can be difficult to access fuel, and that the price of fuel is often too expensive. In many cases, they explained that they needed to buy fuel from the black market, which has even more elevated costs. Thus, farmers expressed needed machinery with good fuel economy.
2. *Engine Horsepower* (N = 22: $P_{\text{no experience}} = 60.0\%$, $P_{\text{experience}} = 66.7\%$). Participants explained that having farming machinery with enough engine horsepower is critical. They explained that higher horsepower can be used on all types of land, particularly the sandy soil where their farms are located. Additionally, the high horsepower engines can help with transportation during the rainy season because most roads are not paved and traversing through the rainwater can be difficult. In fact, when asked a follow-up question of how important they perceived tractor horsepower, 23 said very important, 12 said important, 1 said they weren't sure, and no one said it was unimportant.
3. *Easy to Fix and Not Complicated* (N = 8: $P_{\text{no experience}} = 16.7\%$, $P_{\text{experience}} = 50.0\%$). The farmers explained that they are looking for machinery that they can easily fix by themselves

or at a local mechanic shop, so they can keep the maintenance costs minimum. Similarly, low complexity means they can operate and maintain the equipment easier.

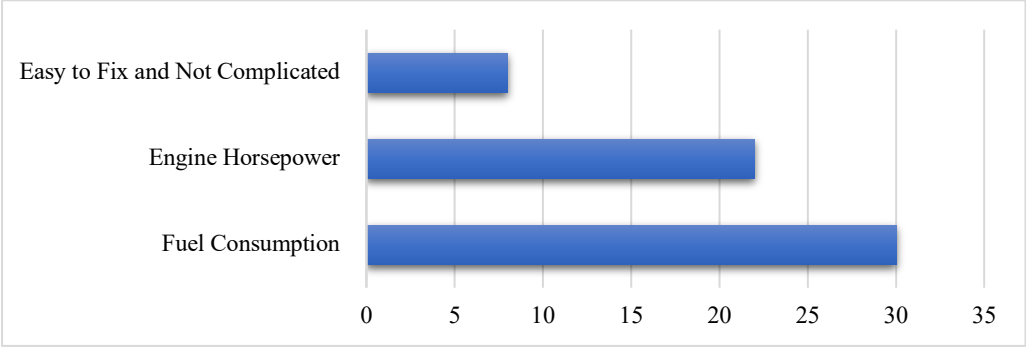


Figure 17. Tractor Design Preferences

Prior to data collection, the research team reviewed various tractor designs and features. The most common design alternatives were aggregated, and each farmer was asked about their preferences on each feature, see Table 51. For each design option, participants were able to select one of the provided options or say they were unsure and not select any option. Chi-square tests of independence (for contingency tables greater than 2x2) and Fisher's exact test (for 2x2 contingency tables) were used to compare responses within each design feature between the no experience and experience groups. For each of the seven design features, the preferences for design options were independent of experience group, indicating that there was no statistical difference between the no experience and experience group in terms of design option preference. Specifically, the results of the Chi-square tests were as follows: engine horsepower $\chi^2(3, N = 36) = 1.859$, $p = .602$; transmission type $\chi^2(2, N = 36) = 1.854$, $p = .396$; min number of cultivator teeth $\chi^2(4, N = 36) = 3.017$, $p = .555$; air conditioning $\chi^2(2, N = 36) = 0.6$, $p = .741$. The results of the Fisher's exact tests were as follows: engine fuel type ($p = .431$); number of wheels ($p = .99$); driver cab ($p = .535$).

Table 51. Tractor Feature Preferences

Design Feature	Design Options	Combined *N (%)*	No Experience *N (%)*	Experience *N (%)*
Engine Horsepower	25 - 50 hp	2 (5.6%)	1 (3.3%)	1 (16.7%)
	50 - 75 hp	26 (72.2%)	22 (73.3%)	4 (66.7%)
	75 - 100 hp	7 (19.4%)	6 (20%)	1 (16.7%)
	> 100 hp	1 (2.8%)	1 (3.3%)	0 (0%)
Engine Fuel Type	Diesel	33 (91.7%)	28 (93.3%)	5 (83.3%)
	Gas	3 (8.3%)	2 (6.7%)	1 (16.7%)
Transmission Type	Manual	33 (91.7%)	28 (93.3%)	5 (83.3%)
	Automatic	2 (5.6%)	1 (3.3%)	1 (16.7%)
	Not Sure	1 (2.8%)	1 (3.3%)	0 (0%)
Number of Wheels	Two-Wheels	2 (5.6%)	2 (6.7%)	0 (0%)
	Four-Wheels	34 (94.4%)	28 (93.3%)	6 (100%)
Min Number of Cultivator Teeth	4 Teeth	2 (5.6%)	1 (3.3%)	1 (16.7%)
	6 Teeth	19 (52.8%)	15 (50%)	4 (66.7%)
	8 Teeth	13 (36.1%)	12 (40%)	1 (16.7%)
	10 Teeth	1 (2.8%)	1 (3.3%)	0 (0%)
	> 10 Teeth	1 (2.8%)	1 (3.3%)	0 (0%)
Driver Cab	Yes	4 (11.1%)	3 (10%)	1 (16.7%)
	No	32 (88.9%)	27 (90%)	5 (83.3%)
Air Conditioning	Yes	2 (5.6%)	2 (6.7%)	0 (0%)
	No	30 (83.3%)	25 (83.3%)	5 (83.3%)
	Not Sure	4 (11.1%)	3 (10%)	1 (16.7%)

Participants were asked to explain why they preferred each design option. An overwhelming majority (94.4%) of the participants indicated that they prefer a four-wheel tractor over a two-wheel tractor. The reasons they cited for this were that they believed four-wheel tractors were: *(1)* easier to operate and have better control (N = 22); *(2)* require far less physical effort to operate (N = 11); *(3)* more efficient and versatile, as they could have many uses (N = 4); *(4)* are less complex (N = 4); *(5)* more familiar since they had no previous knowledge about two-wheel tractors (N = 3); *(6)* more advanced, whereas two-wheels seems too similar to using animals in the farming process (N = 2). The two farmers that said they preferred two-wheel tractors both explained that two-wheel tractors sounded like they would use less fuel.

Similarly, most participants (91.7%) agreed that they would prefer a tractor with a diesel fuel engine over a gasoline powered engine. They explained that: (*1)* diesel engines are easier to fix (N = 21); *(2)* diesel engines are less expensive to operate and maintain (N = 17); *(3)* diesel engines are less complicated (N = 10); *(4)* diesel fuel is available most of the time, unlike gasoline (N = 6); *(5)* diesel mechanics are easy to find (N = 2); and *(6)* they are more familiar with diesel machinery since most of the automobiles in the area run on diesel (N = 2). There were three participants that favored gasoline over diesel, and all three said it was because they thought a gasoline powered tractor would have more power over a diesel.

There was also a majority (91.7%) on choosing a tractor with a manual transmission over an automatic transmission. Similar to the logic behind several other opinions, the top two reasons were that manual transmissions are perceived as less complicated (N = 23) and easier to fix (N = 12). Additionally, two farmers said that they though manual transmissions would be better at farming in rural and uneven areas, especially without paved roads. Two farmers said they preferred

an automatic transmission tractor because they believed it would be easier to operate, and one farmer was not sure which they preferred.

A majority (88.9%) also agreed that they would prefer a tractor without a driver cab. The most common rational for not having a driver cab, was that the cab is unnecessary to the operation of the tractor (N = 19). Followed by a tractor without a cab is less complicated (N = 13) and less expensive (N = 13). However, the four participants that did prefer a tractor with a driver cab said that they valued the comfort the cab would add. Lastly, participants overwhelmingly (83.3%) did not want a tractor with air conditioning, because it would not improve the primary function of the tractor, while decreasing the tractors fuel efficiency.

Participants were also asked about other driver cab media accessories, e.g., Bluetooth, radio, cd player, as many modern farming machineries are equipped with such features. Six of the farmers considered these not at all important, 28 considered them not important, 2 were neutral, 1 said they were important, and none said very important. Specifically, these features were viewed as: *(1)* unnecessarily expensive (N = 14); *(2)* not relevant to tractor operations (N = 14); *(3)* unnecessary luxuries (N = 11); *(4)* useless (N = 10).

6.6 Deciding Factors to Use Tractor Machinery

Each farmer was asked to describe the major deciding factors for them to determine using (rent or buy) a tractor. They were given four factors, plus an "other, please explain" option. None of the participants had an additional reason (i.e., other, please explain). Their explanations for how and which factor influenced their decision were as follows, and as shown in Figure 18:

1. *Cost of Machinery* (N = 29: $P_{\text{no experience}}$ = 76.7%, $P_{\text{experience}}$ = 100%). Almost every participant indicated that the cost of farming machinery is a critical factor, and that whether they rent or buy, it must be priced within their ability to pay.

2. *Financing* (N = 18: $P_{\text{no experience}} = 50\%$, $P_{\text{experience}} = 83.3\%$). Half of the participants described their limited sources of funding, which is primarily and often exclusively from when they sell their farming produce at the end of each farming season, or from selling products from their livestock. Many mentioned that they would consider getting a loan to pay for the machinery, but they would need to be sure that their farming return would be enough to cover the loan payments.
3. *Farm Size* (N = 8: $P_{\text{no experience}} = 16.7\%$, $P_{\text{experience}} = 50\%$). Participants explained that they would need their farm to be large enough to make it worth buying machinery, and also to yield enough return to pay for the machinery.
4. *Machinery Maintenance and Training* (N = 2: $P_{\text{no experience}} = 3.3\%$, $P_{\text{experience}} = 16.7\%$). Only two participants were concerned about the after-market expenses, such as maintenance, training, and technical support for the machinery.

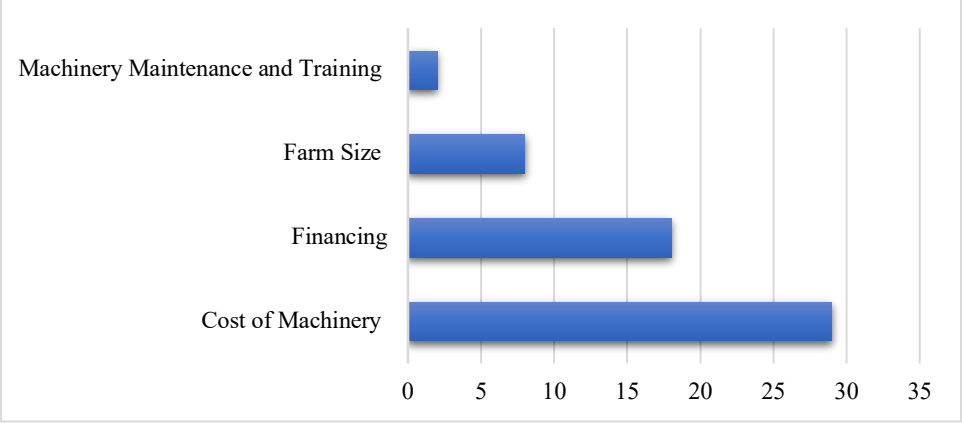


Figure 18. Deciding factors to use Tractor machinery

6.7 Accessories on Farming Machinery

Most of the modern farming machinery, at least in the industrialized countries, comes with accessories such as Bluetooth, Radio, CD Player, ... etc. A majority (76%) of the surveyed farmers believed that these features are not necessary for any farming machinery, which are summarized below:

1. Accessories are considered not important at all because they are just luxuries.
2. Accessories do not add anything to the machinery.
3. Accessories will make the machinery price more expensive.
4. Accessories have nothing to do with the actual operations.
5. Farmers basically do not care about such accessories.

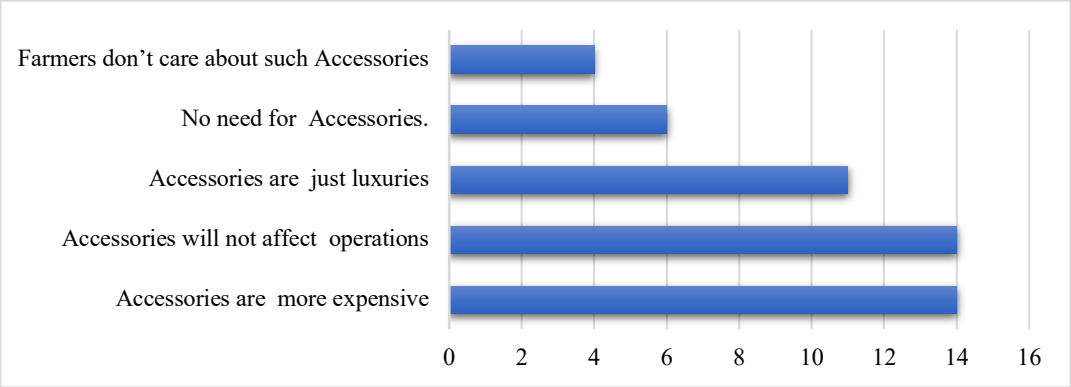


Figure 19. Reasons For not to Have Accessories on Farming Machinery

6.8 Design Validation

The farmers' design preferences were compared to market available machinery. Then, to determine the viability of these options, two cost models were developed.

6.8.1 Market Comparison

There are several tractor manufacturers available in the international market, and the prices of each depend on their design characteristics. The large agricultural manufacturing companies, that are particularly popular in more developed countries, include John Deere, New Holland, Caterpillar, and Massey Ferguson. The average price for a compact tractor (i.e., small tractor with 25 to 75 horsepower) ranges from $35,000 to $55,000 USD. In contrast, smaller agricultural manufacturers in Asia, such as Shandong Hightop Machinery in China, sell compact tractors at an average price of $3,000 to $10,000 USD; hence, making it more reasonable for traditional farmers in Sudan and similar developing economy countries to consider.

There are several compact tractors available on the market that would meet the needs of farmers in Sudan. To encourage adoption, the machinery should fit their needs while being within budget. As a case study, we searched for such a reasonably priced tractor that satisfied this condition, which is summarized in Table 52. The tractor specs were acquired from the company's website for their HT 504 50hp 4wd mini farm tractor (Hightop Group, nd).

Table 52. Comparing Farmer's Needs to Tractor Available in Market

Design Feature	Farmer Preference	High-top Tractor (HT 504)
Engine Horsepower	50 -75 hp	50 hp
Engine Fuel Type	Diesel	Diesel
Transmission Type	Manual	Manual
Number of Wheels	Four-wheels	Four-wheels
Min Number of Cultivator Teeth	6-teeth	Can operate 6 teeth cultivator
Driver Cab	No	No
Air Conditioning	No	No
Price	--	$3,800 USD

6.8.2 Payoff Models

This dissertation considers two payoff model options: (1) farmer uses entire profit that farming with a tractor yields above and beyond their expected return from farming without machinery (labeled as "Entire Δ Profit") and (2) farmer uses a percentage of their total net-profits for the farming season from farming with machinery (labeled as "Percentage of Total Profit"). In the case of Entire Δ Profit, we use values as described in Chapter 5, which provides differences in net-profits (i.e., total returns – total costs) in 2019-2021 farming seasons of farmers in Sudan using farming tractors (labeled as "experience" group in this paper) and comparable farmers in Sudan not using tractors (labeled as "no experience" group in this paper). In the case of Percentage of Total Profit, we use the values as described in Chapter 5, but instead of the differences in net-profits between the two groups, we use the net-profit values from the farmers using the tractors ("experience" group). Further, to account for variability, we calculate both payoff models based

on a 95% confidence interval (CI) for each value, to yield an upper and lower 95% CI estimate (i.e., expected best- and worst-case payoff scenarios). Farm sizes used in the models are based on values reported in Table 50. The payback time is based on the tractor described in Table 51, but the calculation could be adapted for any tractor.

For the Entire Δ Net-Profit model, the lower bound, mean, and upper bound values for farm size and Δ Net-Profit were multiped together to yield the additional net-profit for a farming season associated with using a tractor (labelled "Annual Δ Net-Profit"). The average increase in income for a farm is $970.36 [444.77, 970.36] per year from using a tractor. Thus, it would take an average of 3.92 [2.34, 8.54] years to pay back $3800. These values are shown in Table 53.

Table 53. Payback Model for Entire Δ Net-Profit

Variable	**Farm Size,** *(acres)*	**Δ Net-Profit,** *($/acre)*	**Annual Δ Net-Profit,** *($/year)*	**Payback of $3800,** *(years)*
Lower 95% CI	38.08	11.68	444.77	8.54
Mean	44.39	21.86	970.36	3.92
Upper 95% CI	50.7	32.03	1623.92	2.34

For the Percentage of Total Profit model, a similar mathematical approach was considered. However, instead of the difference between farming with and without a tractor ("Δ Net-Profit"), total net-profits for farming with a tractor were used. In the interviews, each farmer was asked what percentage of their total net-profit they would be willing to put towards buying a tractor (labeled "Willingness to Pay"). Responses ranged from 20% to 41% with an average of 32.89% and standard deviation of 6.05%. The product of farm size, willingness to pay, and total net-profit

yielded the amount of money available to pay towards the tractor each year (labeled "Available to Pay"). On average, farmers using machinery would be able to pay $832.24 [595.57, 1120.75] per year, which would equate to an average of 4.57 [3.39, 6.38] years to payback the $3800 tractor. These values are provided in Table 54.

Table 54. Payback Model for Percentage of Total Profit

Variable	Farm Size, *(acres)*	Willingness to Pay, *(%)*	Total Net-Profit, *($/acre)*	Available to Pay, *($/year)*	Payback of $3800, *(years)*
Lower 95% CI	38.08	30.91	50.61	595.73	6.38
Mean	44.39	32.89	57.00	832.24	4.57
Upper 95% CI	50.7	34.86	63.40	1120.75	3.39

6.9 Chapter Discussion and Summary

This chapter presented the findings from the interviews regarding design needs and built on the net-profit differences identified in Chapter 5. Responses were compared between farmers with and without machinery experience, labeled as "experience" and "no experience" groups. There were no statistical differences ($p < .05$) between the two groups, indicating that the farmers without experience using machinery had similar preferences as those with experience.

Most of the farmers preferred the option to own a tractor over renting one. This was because it would give them the ability to manage the machine the way they wanted to, without any restrictions. Ownership also meant that they could sell the tractor if necessary and regain part of their investment. Participants described their ideal tractor design to be simple, inexpensive, fuel efficient, familiar to repair, and provide multi-utility to farming processes. When farmers expressed simplicity in design, they described utilitarian designs, only wanting to pay for features

directly relevant to the tractor's primary functions. However, they also desired a balance between utilitarian and advanced machinery, saying they did not want a tractor that was similar enough to using animals. Interestingly, none of the farmers mentioned safety as a feature or motivating factor towards machinery adoption. Whereas Pickett et al. (2012) concluded that safety features are one of the most important factors that farmers should consider in agricultural machinery designs.

While it is important to match machinery design to preferences and needs to encourage machinery adoption, there's also an opportunity to demonstrate the usefulness of alternative tractor designs. Farmers might be hesitant to purchase machinery that does not meet their perceptions of necessity, however alternative designs might provide sufficient utility. For example, in our study, participants overwhelmingly preferred four-wheeled tractors, yet Kahan et al. (2018) demonstrated that four-wheeled tractors were not feasible for smallholder farmers in Africa. Hence, the results of this study indicate an opportunity to educate farmers where their perceptions of design differ from importance of design feature.

Another crucial component to mechanized farming adoption, is the economic feasibility for the farmers. The average farm in our study was 44.39 acres, with the smallest farm at 20 acres and the largest at 120 acres. Similar to the average farm size in our study, the farmers reported than they would consider using farming machinery for an average farm size of 44.58 acres (min 0, max 60). This supports that their responses to the tractor design questions were relative to farms of their size. The farmers also reported that they would be willing to pay, on average, 32.89% of their total net-profits towards farming machinery. Based on total net-profits from farming with machinery for these farmers, as reported in Chapter 5, that would equate to an average of $832.24 per year for farming machinery payments, 95% CI of $444.77 to $1623.92. Similarly, if farmers put all the additional profits from farming with machinery over their baseline profits, they would

have, on average, $970.36 per year for farming machinery payments, 95% CI of $595.73 to $1120.75. These two payback models provide similar results, validating the feasibility of farmers to pay off a tractor in a reasonable amount of time. The estimated lifetime of a tractor is 15-years (Li et al.,2018); thus, with the average payments of $970.36 per year over 15-years they could afford a tractor just under $15,000. However, a tractor far exceeding this cost could be of concern for them, and would require additional support, such as families sharing a tractor or government aid.

One limitation of this chapter's analysis is the assumption of a zero-interest loan for the machinery. Loan rates vary greatly, and these cost models are intended to be independent of loan rates. Hence, the models should be adapted to account for loan rates in practical application. There are several financial initiatives available to smallholder farmers in developing economy countries. For example, the Agricultural Bank of Iran, China, Sudan, Malaysia, and Indonesia provide financial support specifically for farmers by offering flexible loans (Meutia et al., 2017).

6.10 Chapter Conclusions

The results presented in this chapter can help guide agricultural machinery design and help inform farmers regarding expected costs, returns, and payoffs from tractor adoption. Further, the methods presented in this chapter can be applied in other regions to capture farmer needs and payoff models for other machinery designs. For example, there are several other countries in Africa that have very low rates (less than 17.5%) of access to tractor-powered machinery (Kirui, 2019), and could economically benefit from agricultural mechanization. These results can be used to prioritize machinery design based on preference and expected return on investment, to encourage farmers in developing economy countries to adopt machinery that fits within their budget and help them develop a reasonable payment plan.

Chapter 7

GENERAL CONCLUSIONS & SUGGESTIONS

This chapter provides an overall summary of the findings from this dissertation, the relevance and dissemination of these results, and future research and applications of the study methodology.

7.1 Overall Finding

The objective of this dissertation was to utilize the Systems Engineering framework to identify Human-Systems Integration opportunities in agricultural practices in Sudan, Africa, which could more broadly be applied to any similar developing economy country. The HSI approach used in this study focuses on evaluating current traditional farming practices, initial perceptions of technology, and concerns regarding adoption, which were then used to identify how technology could be adapted to better achieve long-term, sustainable use by the farmers. The duration of this study was three farming seasons, where thirty-six farms across Sudan were randomly recruited for inclusion in this study, to understand their current farming practices and quantify differences between mechanized (N = 6) and not mechanized (N = 30) farming. The farms were balanced across the different regions in Sudan (North, East, and West), to capture different farming styles, crops, and climate, and ultimately a range of farming profitability. The treatment group was provided with agricultural machinery to assist in the farming process. The key findings from this dissertation are summarized below:

- There was an initial resistance to using agricultural machinery in the first farming season, but afterward, all of the farmers were pleased by their experience with the machinery in the farming process. Exposure to the equipment for the duration of this study appears to be enough to

encourage traditional farmers for the long-term machinery adoption. However, the results of this study suggest that technology adoption likely isn't far, due to the increasing difficulty of hiring laborers and a shifting attitude towards technology acceptance by the children of these farmers.

- A shared challenge identified by all the farmers was the variability in the value of the Sudanese local currency (Sudanese Pound, SDG). This was demonstrated in this study by converting the Sudanese Pound to the US Dollar (USD), which is a more stable and more widely relatable to the average reader. However, in the case of Sudan, there are two exchange rates, the official rate followed by the government and banks, and the black-market rate that the local [farming] economy is based on. The black-market value often deviates significantly from the official-market value, as well as from year to year. As a result, the costs, especially of farming inputs, and revenues, particularly value paid for product, leads to inconsistency for the farmers. This uncontrolled exchange rate negatively effects the country's general economy, limiting the country's ability to support its farmers and other economic sectors. Moreover, tractors are likely imported and paid for at official exchange rates, so it is important to consider how farmers might perceive these different values of the SDG.
- Labor shortages and high costs were also identified by most of the farmers as having a significantly negative impact on their farming net-profits. However, farmers using the machinery required significantly fewer human workers throughout the process, which was one of the major causes for the difference between the farming groups' net-profits and ROIs. Even with the cost of fuel included in the cost of farming with machinery, which we found to add, on average, an extra $3.65/acre for the entire farming season, mechanized farming provided an advantage.

- The financial data for the same three farming seasons, 2019, 2020, and 2021, were gathered for all 36 farms in the study. All the farmers, regardless of machinery group assignment, used traditional farming (i.e., no machinery) in the 2019 season. Since there was no statistically significant difference between the farming groups' costs, revenues, net-profits, and ROIs for 2019, it is fair to assume that the treatment group would have experienced similar financial values to the control group if they had not had access to the machinery. Hence, the observed differences in 2020 and 2021 that we observed in our study between the two groups is most likely due to mechanized farming practices. The analysis on the control group for the 2019 – 2021 farming seasons highlights how farming costs and revenues are largely dependent on the economic measure (i.e., black-market exchange rate); as evident by the fluctuations in costs and revenues despite the consistent farming practices for this group. The use of farming machinery helped lower costs and increase revenues enough to help overcome much of these deficits. In both 2020 and 2021, the treatment group reported significantly higher net-profits and returns on investment than the control group for each respective year. The net-profit per acre increased by 62.30% in 2020 ($43.27/acre vs. $26.66/acre) and by 62.01% in 2021 ($70.74/acre vs. $43.64/acre) for the farmers with machinery compared to those without machinery.
- The ROI increased by 86.7% in 2020 (248.9% vs. 133.3%) and by 96.3% in 2021 (316.4% vs. 161.2%) for the farmers with machinery compared to those without machinery. Follow-up interviews with the farmers indicated that the machinery helped increase these values by: (1) decreasing space between plants, resulting in increased farmed area; (2) enabling farmers to harvest their entire crop on time; and (3) increasing soil aeration, leading to better crops. The

financial gains per acre identified in this study can be used in future work to inform tractor design requirements.

- This study builds on this previous research by quantifying the monetary improvements realized through farm mechanization, which can be used in modeling purchase plans, outreach to farmers, and setting cost thresholds for equipment. While we were able to estimate the cost of fuel based on three farms, this data was limited.
- Owning a farming machinery is a preferable option for traditional farmers as 89% of them prefer owning to renting machinery as owning any farming machinery will give the farmers the ability to manage the machine the way they want without any restrictions, what will give them full control over the machinery in all aspects (selling it, maintenance, lending it, or renting it to other people). There are deciding factors that farmers will consider incase if they want to adopt a farming machinery; these factors are Machinery cost as the most essential factor, source of funding, their farm's size, after-buy services, and the right machinery design.
- Traditional farmers have identified nine features as the most important feature that needs to be in any farming machinery for them to consider the adoption of the machinery. The feature are (1) the machinery's Fuel consumption as it has to be low, (2) The machinery has to be less complicated and easy to fix locally without needing sending them anywhere, (3) the machinery has to have four wheels to be easy to operate, (4) Farmers prefer a machinery without operator cabinet to avoid the high price of the machinery, (5) The average machinery engine horsepower that the farmers desire is between 50 – 75 horsepower so that they can use the machinery for any additional work that required more horsepower, (6) Because the diesel fuel is more available compare to gasoline fuel, farmers prefer to use machinery with diesel engines, (7) The desired transmission Type by farmers is the manual transmission as they think it’s less

complicated, (8) to achieve efficient and quick land preparation, farmers preferer machinery with attached Cultivator that has six teeth.

- Most of the in-market farming machinery comes with accessories features such as Bluetooth, Radio, CD Player, ... etc. Traditional farmers believe that these features are not necessary for any farming machinery because these accessories are not needed to operate the mercenary, and accessories don't add anything to the machinery, but it will make the machinery price more expensive.

7.2 Suggestions

As an outcome of this study, several suggestions have been presented:

1. A policy needs to be developed in collaboration between by the local communities, local authority, and governments that will encourage the traditional farmers to adopt farming technology to achieve long-lasting farming machinery adoption what will result in improving the overall people life's and improve countries general economy.
2. In order to overcome the challenges posed by technology adoption and decrease rural poverty, education on modern equipment should be provided, alternatives to single farmer ownership of equipment should be explored, and maintenance for equipment should be made more accessible.
3. After-buy farming machinery care is one of the most important parts of convincing traditional farmers to use farming machinery of any kind. The after-buy services include ensuring the maintenance and quality of their purchase and access to fuel stations. These services need to be provided by local authorities or by private sectors who are willing to invest in these services, but local authorities need to make such investments more convenient to attract private investors.

4. It is essential to educate farmers on contemporary farming technology, and technological education is crucial since it can efficiently improve farmers' way of life. A strategy for reaching out to as many traditional farmers as possible is required by farming groups in order to deliver farming advanced knowledge. Since it has so many applications, technology is undoubtedly all around us. Despite the fact that many individuals prefer to stick with tried-and-true farming practices, integrating technology into farming opens up a world of opportunities.
5. In order to achieve the aims of financial inclusion for traditional farmers, traditional farmers need access to financial institutions that can provide financial services for rural and smallholder farmers are essential. There is potential development in providing financial services to these unbanked clients (traditional farmers), but to take advantage of prospects in rural areas, their conventional practices must be modified. Microfinance Institution and banks require a long-term strategic commitment, looking beyond just product creation and into adjustments to staffing, operational methods, and credit evaluation. In order to provide recommendations and direct MFIs and banks in all regions to reach this untapped, Traditional farmer’s client base more effectively.
6. Creating a safe, secure environment is critical for farmers so they can practice their farming. Farmers should avoid making themselves easy pickings for a possible farm attack by creating a link with the local police or security services. When farmers have a sense of security and stability, they will be willing to invest more to improve their farming habits, knowing that every investment that they make is actually an asset to them, and no one can change that fact by taking it away from them.

7. Farming machinery manufacturers need to manufacture types of machinery that are suitable for different types of people and acknowledge that different people need different machinery that will satisfy their needs based on their culture, education, and people's financial situation. Doing so will increase the machinery manufacturers' business, and it will help encourage traditional farming in machinery adoption.

7.3 Contributions

This study has three main contributions:

- Utilize the Systems Engineering framework to identify Human-Systems Integration opportunities in agricultural practices in developing economy countries. The HSI approach used in this study focuses on evaluating current traditional farming practices, initial perceptions of technology, and concerns regarding adoption, which were then used to identify how technology could be adapted to better achieve long-term, sustainable use by the farmers through quantitative evidence.
- Examine the profitability of both farming systems: traditional farming without using any machinery and more modern farming using machinery. The approach used in this study focuses on the economic evaluation of the current traditional farming practices and then comparing it with the economic analysis for farming with farming machinery to identify if the use of agricultural machinery could be adopted to improve the financial situations of traditional farmers for long-term and use it as an indication of farmers willing to pay to use or rent the appropriate farm mechanization.
- Addressing the traditional farmer's views about the available in-market farming machinery and identify the general machinery designs that the traditional farmers are looking to see so that they can adopt farming machinery in their farming process as an alternative to the

traditional farming process (farming without machinery). The likely benefits associated with finding and/or developing machinery that integrates with their needs include improving farmers well-being by increasing income and lowering poverty among traditional farmers and providing employment opportunities for nonfarmers who will facilitate using farming machinery.

7.3.1 Publications

This work has been structured into four publications. These publications are summarized as follows:

1. "Human-Systems Integration of Agricultural Machinery in Developing Economy Countries: Perceptions of Adoption" was presented at and published in the INCOSE Human Systems Integration Conference (doi.org/10.1002/iis2.12868). The objective of this paper was to summarize the initial perceptions of farming machinery and barriers to adoption.
2. "Quantifying the Economic Impact on Farmers from Agricultural Machinery: Sudan as a Case Study" has been submitted for publication at a peer reviewed journal and is currently awaiting feedback from reviewers. The objective of this paper was to identify the major influences on farming costs and profits and quantify how the use of machinery effects costs, revenue, net-profits, and returns on investment.
3. "Needs and Requirements Analysis on Tractor Design for Traditional Farmers in Sudan" has been submitted for publication at a peer reviewed journal is currently awaiting feedback from reviewers. The objective of this paper was to identify general tractor design requirements and develop payback models for tractor adoption by farmers.

4. “Factors Influencing Smallholder Farmers and Traditional Farmers in Developing Economy Countries to Adopt Modern Agricultural Technology" was submitted for publication at a peer reviewed journal and is currently awaiting feedback from reviewers. The objective of this paper was to provide a review of the effects and considerations of agricultural technology for smallholder farmers in developing economy countries.

7.4 Limitations and Future Research

One limitation of this study is the duration of the study and sample size. There was one year of baseline farming data and two years of treatment/control farming comparison. Further, there was only enough machinery provided to include six farms in the treatment group. Hence, these results are limited to changes in perceptions related to the farming process for two farming seasons. Evaluation of machinery across a longer farming period could yield further insights into opportunities for increasing adoption. Additionally, providing farmers with equipment for more than two season could also capture long-term shifts in willingness to adopt technology, as there could be an initial learning process for using the equipment. Future research can utilize a similar framework and validate results across additional farmers or in other regions.

Another limitation to machinery adoption is that there is a concern that the extra production from a farm might not be sold (i.e., increased supply not matching demand), causing the farmers to actually lose money and not capture the full benefit of machinery. In Sudan, and many similar developing economy countries, there is quite a lot in the literature about shortages in food production and the huge gap between local food consumption and local food production. Based on these, it suggests that if there is more annual food production, then it will be met by demand via local consumers or by the

government to export to overseas consumers, as exporting agricultural productions is the main source of the national income for Sudan and many other developing economy countries. That being said, I think this is a great opportunity for future follow-on work, on how farming machinery adoption will affect the balance of food supply and demand.

Another limitation is that there are likely other costs associated with farm mechanization, such as accessing fuel and servicing the equipment. Hence, future decisions based on the increased net-profits calculated in this study due to mechanized farming should factor in additional costs that might need to be incurred by the farmers for operating and maintaining the machinery, should that fall on the individual farmers. Additionally, future work could use a similar framework to analyze ROI for various tractor designs, by factoring in the cost of various tractors.

One of the limitations for this study is that it does not include the cost of equipment, the cost of any new storage facilities that might be needed for equipment, and the cost of any chemicals that might use in the farming process, when calculating the return-on-investment ROI. This cost needs to be factored in to get more long-term factors to machinery adoption.

Another way to make farming machinery adaptable is by consolidating small family farms into larger farms so that farmers would have more economic mean of buying/using farming machinery, but this solution has some concerns and negative impact on farmers such as consolidation into larger farms means that fewer people can be farmers also Consolidation works to increase farming's exclusivity, and this has the biggest effect on the local populations that are already underrepresented in establishing agricultural policies.

Future work that can also be done to measure the impact of adoption farming machinery by traditional farmers is by conduction a survey and see how adopting a desirable farming machinery would impact farmers life by quantifying the economic benefit or quality of life benefit of each design preference and seeing how that changes people's opinions on tractor design.

REFERENCES

(USAID), U. A. f. I. D. (2016). Scaling up of agricultural machinery in Bangladesh: Review of successful scaling of agricultural technologies. *E3 Analytics and Evaluation Project, Washington DC, E3*.

Agency, C. I. (2009). *The CIA world factbook 2010*: Skyhorse Publishing Inc.

Agency, C. I. (2013). *The World Factbook 2012-13*: Central Intelligence Agency.

Ahram, T. Z., Karwowski, W., Amaba, B., & Obeid, P. (2009). *Human systems integration: Development based on SysML and the rational systems platform.* Paper presented at the IIE Annual Conference. Proceedings.

Al Hayek, M. A. (2018). The relationship between sales revenue and net profit with net cash flows from operating activities in Jordanian industrial joint stock companies. *International Journal of Academic Research in Accounting, Finance and Management Sciences, 8*(3), 149-162.

Alene, A. D., & Coulibaly, O. (2009). The impact of agricultural research on productivity and poverty in sub-Saharan Africa. *Food Policy, 34*(2), 198-209.

Bationo, A., & Waswa, B. (2011). New challenges and opportunities for integrated soil fertility management in Africa. In *Innovations as key to the green revolution in Africa* (pp. 3-17): Springer.

Baudron, F., Sims, B., Justice, S., Kahan, D. G., Rose, R., Mkomwa, S., . . . Moges, G. (2015). Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheel tractors, conservation agriculture, and private sector involvement. *Food Security, 7*(4), 889-904.

Bauer, M., & Craig, I. K. (2008). Economic assessment of advanced process control–a survey and framework. *Journal of process control, 18*(1), 2-18.

Bechar, A., & Vigneault, C. (2016). Agricultural robots for field operations: Concepts and components. *Biosystems Engineering, 149*, 94-111.

Belal, E. A., Abdallah, F. E., Qishuo, D., Abaker, M., & Talha, Z. (2015). Role of animal traction in agricultural development in Zalingei area, Darfur-Sudan. *Veterinaria, 3*(1), 22-27.

Berhe, G. H. (2016). Impact of agricultural technology adoption of small holder farmers on wheat yield: Empirical evidence from Southern Tigrai State of Ethiopia. *Journal of Agricultural Extension and Rural Development, 8*(10), 211-223.

Biggs, S., Justice, S., & Lewis, D. (2011). Patterns of rural mechanisation, energy and employment in South Asia: reopening the debate. *Economic and Political Weekly*, 78-82.

Borras Jr, S. M., Hall, R., Scoones, I., White, B., & Wolford, W. (2011). Towards a better understanding of global land grabbing: an editorial introduction. *The Journal of Peasant Studies, 38*(2), 209-216.

Botchkarev, A., Andru, P., & Chiong, R. (2011). A return on investment as a metric for evaluating information systems: taxonomy and application. *Interdisciplinary Journal of Information, Knowledge, and Management, 6*(6), 245-269.

Boy, G. A., & Narkevicius, J. M. (2014). Unifying human centered design and systems engineering for human systems integration. In *Complex systems design & management* (pp. 151-162): Springer.

Callo-Concha, D. (2018). Farmer perceptions and climate change adaptation in the West Africa Sudan savannah: Reality check in Dassari, Benin, and Dano, Burkina Faso. *Climate, 6*(2), 44.

Charlton, D., Taylor, J. E., Vougioukas, S., & Rutledge, Z. (2019). Innovations for a shrinking agricultural workforce. *Choices, 34*(2), 1-8.

Davydov, R., Sokolov, M., Hogland, W., Glinushkin, A., & Markaryan, A. (2018). *The application of pesticides and mineral fertilizers in agriculture.* Paper presented at the MATEC Web of Conferences.

Doss, C. R. (2001). Designing agricultural technology for African women farmers: Lessons from 25 years of experience. *World development, 29*(12), 2075-2092.

Duffy, M. (2009). Economies of size in production agriculture. *Journal of hunger & environmental nutrition, 4*(3-4), 375-392.

Ellram, L. M. (2002). Total cost of ownership. In *Handbuch Industrielles Beschaffungsmanagement* (pp. 659-671): Springer.

Erdogmus, H., Favaro, J., & Strigel, W. (2004). Return on investment. *Ieee Software, 21*(3), 18-22.

Ferrin, B. G., & Plank, R. E. (2002). Total cost of ownership models: An exploratory study. *Journal of Supply chain management, 38*(2), 18-29.

Frey, N. (2007). *The effect of responsible tourism management practices on business performance in an emerging market.* University of Cape Town,

Friedrich, T. (2013). Agricultural mechanization and the environment. *Integrated Crop Management, 20*(2013), 181-202.

Gartaula, H., Niehof, A., & Visser, L. (2012). Shifting perceptions of food security and land in the context of labour out-migration in rural Nepal. *Food Security, 4*(2), 181-194.

Gonzales, L. A. (1993). *Economic incentives and comparative advantage in Indonesian food crop production* (Vol. 93): Intl Food Policy Res Inst.

Gregg, E. S., Colton, J., Matin, M. A., & Krupnik, T. J. (2020). Efficient and participatory design of scale-appropriate agricultural machinery workshops in developing countries: A case study in Bangladesh. *Development Engineering, 5*, 100046.

Harris, D. (2019). Intensification benefit index: How much can rural households benefit from agricultural intensification? *Experimental Agriculture, 55*(2), 273-287.

Harris, D., & Orr, A. (2014). Is rainfed agriculture really a pathway from poverty? *Agricultural Systems, 123*, 84-96.

Hassan, T. A. (2015). Economic analysis of factors affecting the farmer income under traditional farming system in South Darfur state–Sudan. *Journal of Agricultural Science and Engineering, 1*(3), 114-119.

Heerink, N. (2005). Soil fertility decline and economic policy reform in Sub-Saharan Africa. *Land Use Policy, 22*(1), 67-74.

Herdt, R. W. (2006). Biotechnology in agriculture. *Annual Review of Environment and Resources, 31*.

Higgins, V., Bryant, M., Howell, A., & Battersby, J. (2017). Ordering adoption: Materiality, knowledge and farmer engagement with precision agriculture technologies. *Journal of Rural Studies, 55*, 193-202.

Hiroyasu, H. (1985). *Diesel engine combustion and its modeling.* Paper presented at the Comodia.

Hutahaean, L., Anasiru, R. H., & Sarasutha, I. (2005). Analisis kelayakan usaha pelayanan jasa alsintan di Sulawesi Tengah. *Jurnal Pengkajian dan Pengembangan Teknologi Pertanian, 8*(1).

Javadi, A., & Rostami, M. (2007). Safety assessments of agricultural machinery in Iran. *Journal of agricultural safety and health, 13*(3), 275-284.

Ji, C., & Wang, S. (2009). Effect of hydrogen addition on combustion and emissions performance of a spark ignition gasoline engine at lean conditions. *International journal of hydrogen energy, 34*(18), 7823-7834.

Johnston, B. F., & Mellor, J. W. (1961). The role of agriculture in economic development. *The American Economic Review, 51*(4), 566-593.

Kamboj, P. (2012). Study of farm machinery services provided by selected cooperative societies. *Agricultural Engineering International: CIGR Journal, 14*(4), 123-133.

Kasirye, I. (2013). Constraints to agricultural technology adoption in Uganda: evidence from the 2005/06-2009/10 Uganda national panel survey.

Keil, A., D'Souza, A., & McDonald, A. (2016). Growing the service economy for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: lessons from custom hiring services for zero-tillage. *Food Security, 8*(5), 1011-1028.

Kienzle, J., Ashburner, J. E., & Sims, B. G. (2013a). *Mechanization for rural development*: FAO.

Kienzle, J., Ashburner, J. E., & Sims, B. G. (2013b). Mechanization for rural development: a review of patterns and progress from around the world. *Integrated Crop Management, 20*.

Krupnik, T. J., Santos Valle, S., McDonald, A. J., Justice, S. E., Hossain, I., & Gathala, M. K. (2013). Made in Bangladesh: scale-appropriate machinery for agricultural resource conservation. In: CIMMYT.

Li, X., Liang, C., Boontanom, J., Martin, D., Ngo, K., Parker, R. G., & Zuo, L. (2017). *Design, fabrication, and testing of wave energy converters (WECs) using different power take-off with mechanical motion rectifier*. Retrieved from

Lowder, S. K., Skoet, J., & Raney, T. (2016). The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World development, 87*, 16-29.

Marcus, A. (2005). User interface design's return on investment: Examples and statistics. In *Cost-justifying usability* (pp. 17-39): Elsevier.

Martin-Clouaire, R., & Duru, M. (2013). Farming system design to feed the changing world. A review. *Agronomy for Sustainable Development 1 (33), 131-149.(2013)*.

Mohamed, I. A. (2010). Assessment of the Role of Agriculture in Sudan Economy.

Morton, L., Hobbs, J., & Arbuckle, J. G. (2013). Shifts in farmer uncertainty over time about sustainable farming practices and modern farming's reliance on commercial fertilizers, insecticides, and herbicides. *Journal of soil and water conservation, 68*(1), 1-12.

Mottaleb, K. A., Krupnik, T. J., & Erenstein, O. (2016). Factors associated with small-scale agricultural machinery adoption in Bangladesh: Census findings. *Journal of Rural Studies, 46*, 155-168.

Mottaleb, K. A., Rahut, D. B., Ali, A., Gérard, B., & Erenstein, O. (2017). Enhancing smallholder access to agricultural machinery services: lessons from Bangladesh. *The journal of development studies, 53*(9), 1502-1517.

Mougeot, L. J. (2000). Urban agriculture: definition, presence, potentials and risks. *Growing cities, growing food: Urban agriculture on the policy agenda, 1*, 42.

Mrema, G., Soni, P., & Rolle, R. (2014). A regional strategy for sustainable agricultural mechanization: sustainable mechanization across agri-food chains in Asia and the Pacific region. *RAP Publication*(2014/24).

Muyanga, M., & Jayne, T. S. (2019). Revisiting the farm size-productivity relationship based on a relatively wide range of farm sizes: Evidence from Kenya. *American Journal of Agricultural Economics, 101*(4), 1140-1163.

Muzari, W., Gatsi, W., & Muvhunzi, S. (2012). The impacts of technology adoption on smallholder agricultural productivity in sub-Saharan Africa: A review. *Journal of Sustainable Development, 5*(8), 69.

Mwangi, M., & Kariuki, S. (2015). Factors determining adoption of new agricultural technology by smallholder farmers in developing countries. *Journal of Economics and sustainable development, 6*(5).

Ocampo, R. O. (2014). Survey and Documentation of the Isnags Traditional Farming Tools and Implements. *Asia Pacific Journal of Education, Arts and Sciences, 1*(1), 1-1.

Pamuk, H., Bulte, E., & Adekunle, A. A. (2014). Do decentralized innovation systems promote agricultural technology adoption? Experimental evidence from Africa. *Food Policy, 44*, 227-236.

Rao, P. P., Birthal, P. S., & Joshi, P. K. (2006). Diversification towards high value agriculture: role of urbanisation and infrastructure. *Economic and Political Weekly*, 2747-2753.

Rousseau, K., Gautier, D., & Wardell, D. A. (2015). Coping with the upheavals of globalization in the shea value chain: The maintenance and relevance of upstream shea nut supply chain organization in western Burkina Faso. *World development, 66*, 413-427.

Samberg, L. H., Gerber, J. S., Ramankutty, N., Herrero, M., & West, P. C. (2016). Subnational distribution of average farm size and smallholder contributions to global food production. *Environmental Research Letters, 11*(12), 124010.

Schmitz, A., & Moss, C. B. (2015). Mechanized agriculture: machine adoption, farm size, and labor displacement.

Selech, J., Ulbrich, D., Kęska, W., Staszak, Ż., Marcinkiewicz, J., Romek, D., & Rogoziński, P. (2019). *Design of a cultivator mounted on a tractor with a power of up to 20 kW.* Paper presented at the MATEC Web of Conferences.

Sharma, N., & Singhvi, R. (2017). Effects of chemical fertilizers and pesticides on human health and environment: a review. *International journal of agriculture, environment and biotechnology, 10*(6), 675-680.

Sheahan, M., & Barrett, C. B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy, 67*, 12-25.

Shen, X., Zhao, X., Ai, P., & Ji, B. (2016). Disadvantages of fertilization in traditional agriculture and development direction of fertilization in modern agriculture. *Journal of Henan Agricultural Sciences, 45*(12), 77-81.

Soechting, F. O. (1999). A design perspective on thermal barrier coatings. *Journal of Thermal Spray Technology, 8*(4), 505-511.

Stringer, L. C., Fraser, E. D., Harris, D., Lyon, C., Pereira, L., Ward, C. F., & Simelton, E. (2020). Adaptation and development pathways for different types of farmers. *Environmental Science & Policy, 104*, 174-189.

Sugiardi, S. (2021). *Economic feasibility analysis of service business of agricultural equipment and machinery in Kubu Raya Regency, Indonesia.* Paper presented at the IOP Conference Series: Earth and Environmental Science.

Tey, Y. S., & Brindal, M. (2012). Factors influencing the adoption of precision agricultural technologies: a review for policy implications. *Precision agriculture, 13*(6), 713-730.

Tinker, D. (1993). Integration of tractor engine, transmission and implement depth controls: Part 1, Transmissions. *Journal of agricultural engineering research, 54*(1), 1-27.

Totin, E., Leeuwis, C., van Mierlo, B., Mongbo, R. L., Stroosnijder, L., & Kossou, D. K. (2014). Drivers of cooperative choice: canal maintenance in smallholder irrigated rice production in Benin. *International journal of agricultural sustainability, 12*(3), 334-354.

Tvaryanas, A. P. (2006). Human systems integration in remotely piloted aircraft operations. *Aviation, Space, and Environmental Medicine, 77*(12), 1278-1282.

USAID. (2016). Scaling up of Agricultural Machinery in Bangladesh: Review of Successful Scaling of Agricultural Technologies*., E3 Analytics and Evaluation Project*(United States Agency for International Development, Washington, DC).

van der Lely, C. (1985). Soil cultivation. In: Google Patents.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R., Mokwunye, U., . . . Shepherd, K. D. (2010). Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on agriculture, 39*(1), 17-24.

Vasilevski, G. (2003). Perspectives of the application of biophysical methods in sustainable agriculture. *Bulgarian Journal of Plant Physiology, 29*(3), 179-186.

Wang, X., Chen, Y., Sui, P., Yan, P., Yang, X., & Gao, W. (2017). Preliminary analysis on economic and environmental consequences of grain production on different farm sizes in North China Plain. *Agricultural Systems, 153*, 181-189.

Wieczorek, A. (2003). Use of biotechnology in agriculture--benefits and risks.

Wilkins, R. J. (2008). Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*(1491), 517-525.

Yadav, G. S., Chandan, D., Datta, M., Ngachan, S., Yadav, J., & Babu, S. (2013). Comparative evaluation of traditional and improved farming practices in Tripura. *Indian Journal of Agricultural Sciences, 83*(3), 310-314.

Yale, T. (2015). List of Traditional Agricultural Equipment: Types and Functions. *Tools Experst Guid*.

Yasnolob, I., Pysarenko, V., Chayka, T., Gorb, O., Pestsova-Svitalka, O., Kononenko, Z. A., & Pomaz, O. (2018). Ecologization of tillage methods with the aim of soil fertility improvement. *Ukrainian Journal of Ecology, 8*(2), 280-286.

Yusuf, S., & Malomo, O. (2007). Technical efficiency of poultry egg production in Ogun state: a data envelopment analysis (DEA) approach. *International journal of poultry science, 6*(9), 622-629.

Zhang, X., Rashid, S., Ahmad, K., & Ahmed, A. (2014). Escalation of real wages in Bangladesh: Is it the beginning of structural transformation? *World development, 64*, 273-285.

Appendix: Translated Interview Questions

Survey: Baseline (April 2020 Treatment Group)

1. Name:
2. Gender:
3. Age:
4. What is your family size?
5. How long have you been farming?
6. What is your farm size (area) in acres?
7. What are the types of crops that you are farming?
8. How many family members are working on the farm?
9. Do you need to hire extra laborers to assist in the farming process?
10. What is the cost per labor? Is it hourly or per day or per area or season?
11. How much is the farming cost per acre?
12. Do you get any support from the local authority?
13. Do you use any machinery at any stage of the farming process? If yes, what kind of machine? If not, why not?
14. Why do you think other farmers are still using traditional farming ways?
15. What is the average income after the season? Is the income enough to meet the family's needs?
16. Who do you sell your crops to? Do you consume your production?
17. How much does it cost to plant one acre?
18. What is the expected return per acre?

19. Does the local authority have any effect on your farming? If yes, how?
20. Have you thought about changing the type of crops that you are farming? Why or why not?
21. What are the problems that you usually face? And how do you overcome them?
22. If you are given a chance to use machinery in all farming processes, are you going to accept that?
23. Do you know any farming technologies that you wish to use? What prevents you from using them?
24. If I am going to suggest a new technology or ideas that might help you to improve the farming process, will you accept them? If not, why not?
25. Can you afford to buy any farming machinery?
26. Have you thought of giving up your farm and switching to anything else?
27. I am planning to help you with using machinery in all the farming process over the season. Will you accept that? If not, why not?

Survey: After Planting (July 2020 Treatment Group)

1- What is the difference between planting this season and the previous seasons after you use the machinery?
2- Was the planting time different this season?
3- Did the cost of planting change after using machinery? Does it increase or decrease?
4- What about the number of laborers difference between this season and the previous seasons?
5- Are you satisfied with the planting process using the machinery?

6- Do you think you will use the machinery in the planting for the next season? And why?

Survey: After Harvesting (September 2020 Treatment Group)

1- What are the differences between harvesting this season and the previous seasons after using the machinery?
2- Does the machinery have any effect on the production amount?
3- Did the cost of harvesting change after using machinery? Does it increase or decrease?
4- Was the harvesting time different this season in comparison to the previous seasons?
5- What about the number of laborers difference between this season and the earlier seasons regarding the harvesting process?
6- Are you satisfied with the harvesting process using the machinery?
7- Do you think you will use the machinery in the planting for the next season? And why?

Survey: Before Planting (April 2021 Treatment Group)

1. Name
2. What do you wish to see different this time? Or what suggestions do you have?
3. What do you think the positive point of using Machinery before the planting season? And what are the negative points?
4. Have you faced any challenges after the previous season?
5. Are there any changes that you want to address this farming season?
6. Has the Machinery addressed your traditional farming concerns?
7. Regarding the land preparation process, do you think the Machinery prepares the land better, or the traditional technique is better in preparing the land? Why?

8. Have you thought about owning farming machinery to do the land preparation? If yes, what steps did you take to do so?
9. Did you operate the farming machine during the land preparation operation? If so? How easy was it to use (scale of 1 to 5)? If you didn't operate it, would you be willing to learn how to operate it?

    1)Very complicated. 2) complicated. 3) Neutral 4) Easy 5) very Easy

Survey: After Planting (July 2021 Treatment Group)

1- Is there any difference between planting this season and last season? If yes, what are the differences?
2- Was the planting time the same as last season?
3- What about the cost of planting in comparison to last season?
4- Have you faced any issues using farming machinery in this planting season?
5- Did you operate the farming machine during the planting operation? If so? How easy was it to use (scale of 1 to 5)? If you didn't operate it, would you be willing to learn how to operate it?

    1)Very complicated. 2) complicated. 3) Neutral 4) Easy 5) very Easy

Survey: After Harvesting (September 2021 Treatment Group)

1- Name?
2- How did the harvesting operation go this season?

3- Are there any issues with harvesting using Machinery? If yes, what are these issues?

4- Has the return similar to the previous season? What are the differences in percent compare to last season?

5- What about the harvesting cost and harvesting time in comparison to the last season?

6- Are you satisfied with using Machinery in the last two seasons?

7- How much farming cost do you think the Machinery will save?

8- Are you going to own farming machinery? And what's your plan to do so?

9- Have you faced any security challenges with using farming Machinery?

10- Have you faced any social challenges with using farming Machinery?

11- Has anyone in your community expressed interest in using the farming Machinery and owning them? Is there any community-organized effort to own farming machinery?

12- Have you had any contact from the local authority regarding this two-seasons farming practice? If yes, what was it about?

13- How did you use the extra time that you had during that last two seasons?

14- What was the impact of using the farming Machinery on your lifestyle and your family?

15- What is your overall idea about using farming machinery over traditional farming operations?

16- If you think using Machinery instead of traditional farming is good, what is the best way to address this point to the rest of the community?

17- With the type of Machinery that you were using these last two seasons? Do you think the machinery design, technology, reliability, or anything relating to the Machinery needs to be changed or advanced?

18- Do you think there are any barriers that will prevent you from owning farming machinery? If yes, what are these barriers?

19- If the farming Machinery would be shared between farmers, How many families do you think could share the farming equipment?

20- What farming tasks do you think are important to use the Machinery for? Or What farming tasks would you rather not use the Machinery for?

21- What functions/features would you most like or not like in a farming machine?

22- Did you operate the farming machine during the Harvesting operation? If so? How easy was it to use (scale of 1 to 5)? If you didn't operate it, would you be willing to learn how to operate it?

1)Very complicated. 2) complicated. 3) Neutral 4) Easy 5) very Easy

23- On a scale of 1 – 5, how do you find the farming Machinery helpful in land preparation? With;

1) Not helpful at all. 2) Not helpful. 3) Neutral 4) helpful 5) very helpful

24- On a scale of 1 – 5, how do you find the farming Machinery helpful in planting operations? With;

1)Not helpful at all. 2) Not helpful. 3) Neutral 4) helpful 5) very helpful

25- On a scale of 1 – 5, how do you find the farming Machinery helpful in crop harvesting operations? With;

1)Not helpful at all. 2) Not helpful. 3) Neutral 4) helpful 5) very helpful

26- On a scale of 1 – 5, how likely are you going to use the farming Machinery? With;

1)Extremely unlikely. 2) unlikely. 3) Neutral. 4) likely. 5) Extremely likely.

27- On a scale of 1 – 5, how did the use farming machinery affect you and your lifestyle? with

1)No effect. 2) – Minor effect. 3) Neutral 4) Moderate effect. 5) Major affect

28- On a scale of 1 – 5, what is the probability that your community will consider using farming Machinery? With;

1) No Chance. 2) – Neutral . 3) High Chance 4) Very Hight Chance

Survey: Machinery Design

1) Name:
2) Gender:
3) Farm Size:
4) How long have you been farming?
5) Have you used any farming machinery? Why? Why not?
6) What do you think are the essential feature of the agriculture machinery?
7) What is the minimum farm size that will lead you to own machinery?
8) What is the main factor that will make you decide to use the farming machinery and adapt it as a way of farming?

1) Fund 2) Machinery cost (to buy or to own) 3) Land Size 4) After-buy services (maintenance, parts, …) 5) The right machinery designs

9) Do you think it's better to own farming machinery or rent them? And why?

1) Own 2) Buy

Why?

10) Do you prefer a four wheels tractor or Two wheels tractor? And why?

1) Four Wheels 2) Two Wheels

Why?

11) Do you prefer a tractor with a cabinet or without a cabinet? And why?

1) Without a cabinet 2) Without a cabinet

Why?

12) How important is the machinery engine horsepower to you if you decide to use them?

1)Very Important. 2) Important. 3) Neutral 4) Not Important 5) Not Important at all

13). What is the range of machinery engine horsepower that you think is suitable for your farm? In terms of the tractor size

1) From 25 - 50 Hp. 2) From 50 - 75 Hp. 3) From 75 - 100 Hp 4) 100 + Hp

14) What type of machinery engine do you prefer? And why?

1) Diesel engine 2) Gasoline engine

Why?

15) Do you prefer to have machinery with manual transmission Or Auto transmission? And why?

1) Manual transmission 2) Auto transmission

Why?

16) How important is it to have an air conditioner AC in the farming machinery?

1)Very Important. 2) Important. 3) Neutral 4) Not Important 5) Not Important at all

- 17) How important is it to have an air conditioner AC in the farming machinery?

1)Very Important. 2) Important. 3) Neutral 4) Not Important 5) Not Important at all

- 18) How important is it to have Bluetooth, Radio, and any accessories in the farming machinery? And why?

1)Very Important. 2) Important. 3) Neutral 4) Not Important 5) Not Important at all

Why?

- 19) How important is it to have two PTO (Power tack-off) in the farming machinery? And Why?

1)Very Important. 2) Important. 3) Neutral 4) Not Important 5) Not Important at all

Why?

- 20) What is the minimum/average number of cultivator's teeth do you think are suitable for your farm?

1) 4 teeth 2) 6 teeth 3) 8 teeth 4) 10 teeth 5) More than 10 teeth

- 21) What is the average overall farming cost in the last three farming seasons? Compare the annual labor cost vs. the annual machinist cost

2021	2020	2019

- 22) What is the average overall farming total profit in the last three farming seasons?

2021	2020	2019

- 23) How much percent out of your total yearly return are you willing to put toward buying farming machinery?