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Needs Analysis and Payback Models for Tractor Design Based on Field Data from Farmers in Sudan

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Abstract: The adoption of agricultural machinery in countries with a developing economy can have a significant impact on improving well-being and pro-poor growth. However, this requires farmers to buy into mechanized farming, which is more likely to happen if the machinery meets their needs. The objective of this paper is to identify deciding factors for traditional farmers to adopt machinery and identify design requirements. Payback models were developed based on these design requirements, willingness to pay, and expected returns. Thirty-six farmers in Sudan were interviewed throughout 2019–2021. Six of these farmers were provided tractors during 2020 and 2021. Differences in net-profits between the 30 control and 6 treatment farms during the mechanized farming seasons were used in the models for expected profits. There were no significant differences in tractor design preferences between the treatment and control groups. Two cost models were estimated using a 95% confidence interval: entire Δ profit (entire additional profit from mechanized farming above nonmechanized) and percentage of total profit (percentage of total net-profits willing to spend). For the average farm size in this study (44.39 acres) and a market available tractor that satisfied all farmer needs, payback was 3.92 years [2.34, 8.54] and 4.57 years [3.39, 6.38] for the models, respectively.

Keywords: Africa; agriculture; developing country; farming machinery; mechanized farming; payback model; tractor design; traditional farmers

Citation: Ahmed, H.; Miller, E.E. Needs Analysis and Payback Models for Tractor Design Based on Field Data from Farmers in Sudan. *World* **2023**, *4*, 698–708. https://doi.org/10.3390/world4040044

Academic Editors: Masoud Yazdanpanah, Tahereh Zobeidi, Mostafa Ahmadvand and Katharina Löhr

Received: 28 August 2023
Revised: 20 October 2023
Accepted: 25 October 2023
Published: 27 October 2023

1. Introduction

Agricultural machinery, like other consumer products, should address the needs of their users. However, it can be challenging to address all client requirements, especially given the competitive demands, complexity, and vast variety of the worldwide agricultural sector [1]. Industrialized countries have long benefited from the use of mechanized farming, and similar adoption offers a viable solution for developing-economy countries to improve their rural economies and address labor shortages [2]. Hence, there is a need for equipment manufacturers to understand the specific needs of these farmers and their farming operational characteristics [1] and integrate these needs into machinery design [3,4].

Previous and recent efforts in farm mechanization have focused on tractor designs to increase engine power, capacity, attachments, and reliability and decrease operating expenses and labor [5]. For example, Xia et al. [6] 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. [7] explored farming machinery designs that integrated solar power to achieve more sustainable farming operations. A few studies have also included some user characteristics in their tractor designs. For example, Yadav et al. [5] measured the strength of 105 agricultural workers to help inform the design of hand and foot controls. Similarly, Vyavahare and Kallurkar [8] 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. While Yadav et al. [5] focused on ergonomics, Vyavahare and Kallurkar [8] focused on machinery efficiency, both of which are important factors for improving operations and decreasing costs. However, these efforts are also too narrowly focused on reducing input costs and increasing crop intensity, and they do not consider other important considerations, such as long-term social, economic, and environmental factors, which could have detrimental effects on small farms in developing-economy countries [9]. Furthermore, in developing-economy countries, many smallholder farmers are hesitant to adopt new and unfamiliar farming technology [10], and marketing the technology to meet their needs could improve adoption rates.

While the abovementioned previous works are 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 in regard to the adoption of this new technology. Hence, this paper develops a framework for identifying needs and encouraging the adoption of farming machinery for traditional farmers in developing-economy countries. This study was conducted in Sudan, Africa, as Sudan has low levels of mechanization and low farming productivity [11], and it is estimated that 60 to 80% of its population works in the agricultural industry [12].

The overall objective of this paper is to utilize a human–system integration approach to farm mechanization in developing-economy countries. 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.

2. Materials and Methods

Interviews were conducted to gather the perceptions of farmers regarding tractor machinery design and thresholds for their willingness to pay. This information was then synthesized to identify potential machinery design solutions. Lastly, cost models were developed to estimate payback durations and expected returns from these investments. This study had Institutional Review Board (IRB) approval prior to data collection.

2.1. Data Collection

Data were collected from farms in Sudan, Africa, during three farming seasons (2019, 2020, and 2021). Six of the farms were provided with a tractor and three tractor attachments (i.e., a cultivator, planter, and harvester) for the final two of the three farming seasons. The other thirty participants were matched based on farming demographics to serve as the control group.

Interviews with each farmer were conducted in Arabic and then translated to English by the research team. At the end of each major farming process (i.e., planting and harvesting), each participant was asked about his/her farming costs (inputs) and profits (outputs). None of the farmers practiced mechanized farming in the 2019 farming season; hence, these values were compared in 2019 for similarity to validate non-mechanized farming costs and profits between the treatment and control groups. Then, reported revenues were compared between groups in 2020 and 2021 to calculate the increase in revenue associated with the use of farming machinery. This is further described in detail in Ahmed and Miller [13]. In this current paper, these values of increased revenue due to using a tractor are used for the cost model calculations.

In addition to the questions about costs and profits, all 36 participants were asked questions about various machinery design alternatives that would motivate them to purchase machinery and how much they would be willing to pay for it. Given that only 6 of the 30 participants had experience with the machinery, their responses were split into participants with experience (treatment group) and without experience (control group), and analytical tests were used to identify if differences in preference appeared to be associated with their machinery experience level.

2.2. Participants

There was a total of 36 farms across Sudan: 6 treatment and 30 control. The treatment group was provided with tractors, training to use the tractors, and fuel to operate the tractors for the 2020 and 2021 farming seasons. Only farmers who practiced traditional farming, without any modern farming machinery, were included in the study. In this paper, farmers in the treatment group are referred to as the group with machinery experience, and farmers in the control group are referred to as the group with no machinery experience. Farms were recruited by visiting tribal leaders and gaining permission to contact the farms within the villages.

2.3. Analytical Methods

Participants provided their responses in both open-ended conversation format and multiple-choice answers, depending on the question. The open-ended conversation responses were summarized into themes, using a content analysis methodology to group similar responses together. For example, when asked what tractor attributes were most important, one participant mentioned the price of fuel being a barrier to adoption, and another mentioned the difficulty of fuel availability, which were then grouped together as tractor fuel efficiency being an important attribute. Each of these merged classifications and underlying themes are further described within the Results section.

Statistical tests were assessed at $\alpha = 0.05$. The analytical tests performed included t-tests, chi-squared tests, and Fisher's exact tests. These tests were used to compare responses between the experience and no-experience machinery groups to determine if design preferences differed based on experience with tractors. In cases where both groups agreed, these design preferences could encourage adoption. The cases where significant differences existed between the two groups represent opportunities for marketing, education, or outreach to address this gap. Specifically, t-tests were performed to compare differences in responses of continuous variables, i.e., minimum farm size they would consider using a tractor on. Meanwhile, the chi-squared and Fisher's exact tests were performed to compare responses of categorical variables, i.e., various design options. Lastly, cost models were computed to estimate payback time for a reasonable tractor design given the design requirements. In these models a 95% confidence interval was computed to provide an estimate for worst-case (upper 95% CI), expected-case (mean), and best-case (lower 95% CI) scenarios for paying off the tractors. All analyses were conducted using Excel (version 16.77.1) and RStudio (version 4.2.2).

3. Results

3.1. Farm Sizes

There were 36 farms included in this study, with an average farm size of 44.39 acres (SD 19.33 acres). Each participant was asked what the minimum farm size would be for him/her to consider using a tractor (mean = 44.58; SD = 10.65; see Table 1). There was no significant difference in the minimum farm size reported to encourage tractor adoption between the group with no machinery experience group (mean = 44.83, SD = 11.19) and the group with machinery experience (mean = 48.33; SD = 6.83), $t(11.253) = 1.302$, $p = 0.219$.

Table 1. Descriptive statistics of farm sizes (acres).

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

3.2. Deciding Factors to Use Tractor Machinery

Each farmer was asked to describe the major deciding factors for him/her 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:

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 he/she rents or buys, it must be priced within his/her 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, and this funding primarily and often exclusively comes 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, as well as 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.

3.3. Owning over Renting a Tractor

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

1. No Restrictions (N = 31: $P_{\text{no experience}}$ = 83.3%; $P_{\text{experience}}$ = 100%). All the participants except for one who 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, and/or rented/lent the machinery. It also meant that they were not in debt to someone, and that if something happened to the equipment, there would not be any external consequences.
2. Asset for Farmer (N = 5: $P_{\text{no experience}}$ = 13.3%; $P_{\text{experience}}$ = 16.7%). Several participants explained that owning the tractor would make it an asset to them and that 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: $P_{\text{no experience}}$ = 3.3%; $P_{\text{experience}}$ = 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.

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 could upgrade if they wanted.

3.4. Tractor Design Preferences

Each farmer was asked an open-ended question to explain what features were most important for a tractor to include for it to be useful to them. Their responses were categorized into three concepts:

1. Fuel Consumption (N = 30: $P_{no\ experience}$ = 76.7%; $P_{experience}$ = 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 the need for machinery with good fuel economy.
2. Engine Horsepower (N = 22: $P_{no\ experience}$ = 60.0%; $P_{experience}$ = 66.7%). Participants explained that having farming machinery with enough engine horsepower is critical, which makes sense, as this relates to tractor performance. They explained that reasonably 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 to be, 23 said very important, 12 said important, 1 said not sure, and no one said it was unimportant.
3. Easy to Fix and Not Complicated (N = 8: $P_{no\ experience}$ = 16.7%; $P_{experience}$ = 50.0%). The farmers explained that they are looking for machinery that they can easily fix by themselves or have fixed at a local mechanic shop, so that they can keep the maintenance costs at a minimum. Similarly, low complexity means that they can operate and maintain the equipment easier.

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 his/her preferences on each feature (see Table 2). For each design option, participants were able to select one of the provided options or say that they were unsure and not select any option. Chi-square tests of independence (for contingency tables greater than 2 × 2) and Fisher's exact test (for 2 × 2 contingency tables) were used to compare responses within each design feature between the no-experience and with-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 the with-experience group in terms of design option preference. Specifically, the results of the chi-square tests were as follows: engine horsepower, $\chi^2(3, N = 36) = 1.859$, $p = 0.602$; transmission type, $\chi^2(2, N = 36) = 1.854$, $p = 0.396$; minimum number of cultivator teeth, $\chi^2(4, N = 36) = 3.017$, $p = 0.555$; and air conditioning, $\chi^2(2, N = 36) = 0.6$, $p = 0.741$. The results of the Fisher's exact tests were as follows: engine fuel type ($p = 0.431$), number of wheels ($p = 0.99$), and driver cab ($p = 0.535$).

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-wheeled tractor over a two-wheeled tractor. The reasons they cited for this were that they believed four-wheeled tractors (1) are easier to operate and have better control (N = 22); (2) require far less physical effort to operate (N = 11); (3) are more efficient and versatile, as they could have many uses (N = 4); (4) are less complex (N = 4); (5) are more familiar to them, since they had no previous knowledge about two-wheeled tractors (N = 3); and (6) are more advanced, whereas two-wheels seem too similar to using animals in the farming process (N = 2). The two farmers who said that they preferred two-wheeled 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 who favored gasoline over diesel, and all three said it was because they thought a gasoline-powered tractor would have more power over a diesel.

Table 2. Tractor design 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%)

There was also a majority consensus (91.7%) in regard to 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 thought manual transmissions would be better for farming in rural and uneven areas, especially without paved roads. Two farmers said that they preferred an automatic transmission tractor because they believed it would be easier to operate, and one farmer was not sure which he/she preferred.

A majority (88.9%) also agreed that they would prefer a tractor without a driver cab. The most common rationale for not wanting a driver cab was that the cab is unnecessary for the operation of the tractor (*N* = 19). This was 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 that 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, and instead, it would decrease the tractor's fuel efficiency.

Participants were also asked about other driver cab media accessories, e.g., Bluetooth, radio, and CD player, as many modern farming machineries are equipped with such features. In total, 6 of the farmers considered these not at all important, 28 considered them not important, 2 were neutral, 1 said they were important, and 0 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), and (4) useless (*N* = 10).

3.5. 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.

3.5.1. Market Comparison

There are several tractor brands available in the international market, and the prices of each depend on their design characteristics. The large agricultural manufacturing companies, which are particularly popular in more developed countries, include John Deere, New Holland, Caterpillar, and Massey Ferguson. The average price for their compact tractor (i.e., small tractor with 25-to-75 horsepower) ranges from USD 35,000 to USD 55,000. In contrast, smaller agricultural manufacturers in Asia, such as Shandong Hightop Machinery in China, sell compact tractors at an average price of USD 3000 to USD 10,000, thus making it more reasonable for traditional farmers in Sudan and similar developing economy countries to consider. We are not specifically endorsing any one manufacturer over another; instead, we are merely demonstrating how to calculate a realistic payback model.

There are several compact tractors available on the market that would meet the needs of farmers in Sudan based on the abovementioned results. 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 3. The tractor specifications were acquired from the company's website for their HT 504 mini farm tractor with 50 hp and 4 wd [14].

Table 3. Comparing farmer's needs to tractor available in market.

Design Feature	Farmer Preference	Hightop 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	-	USD 3800

3.5.2. Payoff Models

We consider two payoff model options: (1) the farmers use entire profit that farming with a tractor yields above and beyond their expected return from farming without machinery (entire Δ profit) and (2) farmers use a percentage of their total net-profits for the farming season from farming with machinery (percentage of total profit). In the case of the entire Δ profit model, we use values as described and published in Ahmed and Miller's study [13], which provides differences in net-profits (i.e., total returns minus total costs) of the farmers using tractors (labeled the with-experience group in this paper) and comparable farmers not using tractors (labeled the no-experience group in this paper). In the case of the percentage of total profit model, we use the values as described and published in Ahmed and Miller [13], but instead of the differences in net-profits between the two groups, we only use the net-profit values from the farmers using the tractors (with-experience group). Furthermore, 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). The farm sizes used in the models are based on values reported in Table 1 (44.39 +/− 6.31 acres). The payback time is based on the tractor described in Table 3, but the calculation could be adapted more broadly 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 (annual Δ net-profit). The average increase in income for a farm is USD 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 USD 3800. These values are shown in Table 4.

Table 4. Payback model for entire Δ net-profit.

Variable	Farm Size (Acres)	Δ Net-Profit (USD/Acre)	Annual Δ Net-Profit (USD/Year)	Payback of USD 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 his/her total net-profit he/she would be willing to put towards buying a tractor (referred to as 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 (referred to as available to pay). On average, farmers using machinery would be able to pay USD 832.24 [595.57, 1120.75] per year, which would equate to an average of 4.57 [3.39, 6.38] years to pay off the USD 3800 tractor. These values are provided in Table 5.

Table 5. Payback model for percentage of total profit.

Variable	Farm Size (Acres)	Willingness to Pay (%)	Total Net-Profit (USD/Acre)	Available to Pay (USD/Year)	Payback of USD 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

4. Discussion

This paper presents the findings from interviews of 36 farmers in Sudan, Africa, who were interviewed regarding their needs and expectations regarding tractor machinery. Increased utilization of mechanized farming practices can improve economic conditions of rural farmers [15]. However, this requires these farmers to buy in, so they need to trust that the machinery can meet their needs and fit within their budget. The average farm size in this study was 44.39 acres, each operated by an individual family and by farmers who farmed using traditional farming practices, i.e., no machinery. Six of the farms were provided with a tractor with attachments for use in the previous two farming seasons. Responses were compared between farmers with and without machinery experience, labeled as the with-experience and no-experience groups, respectively. There were no statistical differences ($p < 0.05$) between the two groups, indicating that the farmers without experience using machinery had similar preferences as those with experience. As such, this increases the validity of these findings, as the relatively small sample converged on tractor needs and requirements.

Most of the farmers preferred the option to own a tractor over renting. 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. Alternatively, some researchers believe that there are opportunities to improve access to mechanization through an "Uber for tractor" model [16], which could change perspectives on ownership or present further benefits to tractor owners.

Fear of economic instability was an underlying theme to many of their responses and rationales, suggesting that outreach, assistance, and aid should focus on quantified economic benefits and bridging potential revenue gaps during repayment periods. In an adjacent application, researchers reported low adoption rates of agricultural technology for irrigation systems in Bangladesh despite visible benefits, largely due to the technologies lack of competitive pricing [17]. Similarly, the availability of components and costs of repair/maintenance can influence the economic viability of adoption. In an interview study of 111 tractor owners/operators in Nigeria, farmers reported spending USD 500 to USD 1000 on maintenance and repairs each year (e.g., tires and fuel supply systems) but were able to address 90% of the needed repairs within their local area [18].

Participants described their ideal tractor design to be simple, inexpensive, fuel efficient, familiar to repair, able to 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. However, Pickett et al. [19] concluded that safety features are one of the most important factors that farmers should consider in agricultural machinery designs. Identifying tractors with sufficient performance and capacity is also necessary. In our study, most farmers preferred a 50–75 hp tractor. Previous research in developing economy countries for similar farm operations indicates that 50 hp [18,20] up to 75 hp [18] provides sufficient power, as well as that tractors of this size can adequately support the necessary farming attachments [18].

While it is important to match machinery design to preferences and needs to encourage machinery adoption, there is 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. [21] 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 the importance of design features.

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. Closely matching their average farm size, the farmers reported that they would consider using farming machinery for an average farm size of 44.58 acres (min 0, max 60). This supports the idea that their responses to the tractor design questions were relative to the size of their farms, i.e., that they were familiar with the operational needs of. The farmers also reported that they would be willing to pay, on average, 32.89% of their total net-profits towards machinery. Based on total net-profits from farming with machinery for these farmers, as reported by Ahmed and Miller [13], that would equate to an average of USD 832.24 per year for farming machinery payments, with a 95% CI of USD 444.77 to USD 1623.92. Similarly, if farmers put all the additional profits from farming with machinery over their baseline profits, they would have, on average, USD 970.36 per year for farming machinery payments, and a 95% CI of USD 595.73 to USD 1120.75. These two payback models provide similar results to each other, validating the feasibility of farmers to pay off a tractor in a reasonable amount of time. Alternatively, other payback models could consider an offset in time to repay, such as Takeshima et al. [18], who reported that farmers saved, on average, for three to five years before purchasing their first tractor. The estimated lifetime of a tractor is 15 years [22]; thus, with the average payments of USD 970.36 per year over 15 years, they could afford a tractor just under USD 15,000. 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. However, other works in the literature suggest that tractors can have a much longer lifespan; for instance, one study tracked purchases of tractors in Nigeria and reported farmers purchasing tractors that were already 17+ years old at the time of purchase [18].

One limitation of this research 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 [23]. Other studies have reported federal and state governments providing 35% subsidies to farmers purchasing tractors [18]. Additionally, there was no estimated cost of each design alternative, availability of components, or estimated impact on fuel consumption when presented to the participants. While participants did not select the simplest design options across the board, indicating that they were not simply aiming for the cheapest designs, it would be interesting to see how much incremental cost farmers are willing to pay for incremental design improvements, which could be estimated using discrete choice modeling. Hence, this research could be extended with monetized choice models presented to farmers. Furthermore, future research could utilize this framework by applying it to other tractors or regions, as there are several other countries in Africa that currently have very low rates (i.e., less than 18%) of access to tractor-powered machinery [24]; hence, there are several similarly applicable markets.

5. Conclusions

The results presented in this paper can help guide agricultural machinery design, particularly for machinery aimed to serve developing country populations with low levels of machinery adoption, as these findings synthesize feedback from a sample of this population. Our findings emphasize the importance of cost-effective solutions and conveying the feasibility of this technology; as such, these results can help inform farmers regarding expected costs, returns, and payoffs from tractor adoption. Furthermore, the methods presented in this paper can serve as a framework and be applied in other regions to capture farmer needs and payoff models for other equipment types and designs. 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. While the findings in this paper may be limited by the tractor design selected for analysis or the design options presented to the participants, the main contribution of this research is the repeatable framework it presents for identifying barriers to the adoption of agricultural machinery. Overall, developing payment plans based on willingness to pay and expected returns offers a viable path towards the sustainable adoption of farming technology for the rural populations of developing-economy countries.

Author Contributions: Conceptualization, H.A.; methodology, H.A. and E.E.M.; validation, H.A. and E.E.M.; formal analysis, H.A. and E.E.M.; investigation, H.A.; resources, H.A. and E.E.M.; data curation, H.A.; writing—original draft preparation, H.A. and E.E.M.; writing—review and editing, H.A. and E.E.M.; supervision, E.E.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of Colorado State University (protocol code 20-9878H and 27 March 2020).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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