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Mechanization in rice farming reduces greenhouse gas emissions, food losses, and constitutes a positive business case for smallholder farmers – Results from a controlled experiment in Nigeria

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A B S T R A C T

In this paper, we present a controlled experiment to assess the impact of a switch to mechanized harvesting and mechanized threshing on smallholder rice farms in Nigeria. We measure how food losses and efficiency compare to manual harvesting and threshing practices, and evaluate the business case of mechanization for smallholder farmers, as well as the effect on total Greenhouse Gas emissions. Furthermore, we discuss observations on the socioeconomic impact of mechanization of farm operations, in particular on the role of women and youth. The experimental results show that mechanized harvesting and threshing not only significantly reduce losses and increase yields per hectare but also have a positive socio-economic impact. Mechanized harvesting and threshing are labor-saving, which lead in the case study to positive impacts, such as freeing up time of women during the busy harvest period for other activities and providing new opportunities for rural youth. A comparison of the costs farmers incur for on one hand manual harvesting and threshing and on the other hand mechanized harvesting and threshing show that mechanization of these activities constitutes a positive business case for farmers: a relatively small cost increase is offset by large by considerable yield (and therefore revenue) increases. Furthermore, when factoring in the fuel use of harvesting and threshing machinery, increased greenhouse gas emissions from mechanized practices are negligible compared to the food loss and waste induced greenhouse gas emissions that are avoided by reducing losses with the more efficient mechanized equipment.

1. Introduction

Food loss and waste is a major contributor to global greenhouse gas (GHG) emissions, and a barrier to food and nutrition security in low- and middle-income countries (FAO, 2019; Guo et al., 2020). In the context of sustainable development and feeding a growing global population, it is desirable to reduce food losses rather than simply increase production and in doing so saving resources and reducing environmental impact (Hodges et al., 2011; World Bank, 2011). While percentagewise food losses are highest among perishable foods such as fruit and vegetables, in terms of volume and impact on vulnerable people's diets, losses in staple foods such as rice are extremely relevant (Guo et al., 2020). Whereas in developed countries the larger share of FLW is food waste at the retail and consumer levels, in developing countries food loss in early stages of the food chain is a major issue (Hodges et al., 2011). It is also mostly in developing countries that food losses have the largest impact on food security and rural livelihoods. In these food systems, production takes place predominantly by smallholder farmers with limited resources and capabilities, on family-run farms comprising at most a few hectares that are worked with mostly manual labor. Improving efficiency and reducing losses at smallholder farms is a major challenge, but offers significant opportunities to address a loss hotspot early on in the chain while also improving food and nutrition security and smallholder farmers' livelihoods. Frequently, use of mechanized farm equipment is discussed as a possible strategy to improve efficiency and reduce losses at smallholder farms. However, low uptake among smallholder farmers and uncertainty regarding the actual impact on losses as well as socio-economic outcomes (e.g. local unemployment and gender disparities) indicate that further research is necessary into how mechanization can robustly improve outcomes in smallholder-dominated food

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systems (Daum and Birner, 2020).

Several questions identified by Daum and Birner (2020) – regarding the benefit of mechanization for smallholders, its environmental impacts, and its effects on land productivity – can be addressed in a more quantitative manner by combining two empirical strategies, namely a controlled experimental setup that helps accurately identify the actual impact of mechanization, and a multidimensional evaluation of outcomes, focusing not only on farm productivity, but also considering the business case for farmers and implications for farmers' communities. This study aims to undertake this approach. In a controlled experiment, we investigate the impact of switching from manual labor to mechanized farm equipment for smallholder rice farms in Nasarawa, Nigeria. We use these experimental findings to evaluate the yield and losses under different technologies, calculate GHG emissions for these scenarios, and evaluate the economic feasibility of various options for mechanization of smallholder farms. Last, we broaden the scope of the study by discussing observations on socioeconomic factors (division of labor, impact on the local economy, and the role of women and youth) made by the field experts conducting the experiment.

This study makes three main contributions. First, we contribute to developing research on postharvest losses and mitigation strategies with a rigorous controlled experimental study on mechanization interventions – a promising domain, but with significant open questions remaining. Secondly, we provide a complete evaluation of the interventions, not only considering yields and food losses, but also food loss-induced GHG emissions and the GHG emissions induced by the intervention, formulating a positive business case for smallholder farmers, and discussing the investigated intervention in relation to the socioeconomic context in the local food system. Third, based on this well-rounded study of mechanization interventions in rice production, we can make targeted and well-founded recommendations for policy and practice.

The remainder of this paper is structured as follows. Section 2 discusses the relevant literature and background of this research, section 3 outlines the experimental setup and data collection process, section 4 presents the results, and section 5 discusses these results. Last, section 6 presents our conclusions and policy recommendations.

2. Background and literature review

Globally, food loss and waste (FLW) accounts for about 8% of anthropogenic Greenhouse Gas emissions (GHG emissions), a share in global emissions larger than that of most countries except China and the United States (FAO, 2015, 2017). Currently, around one third of all food produced worldwide is lost or wasted before it is consumed (FAO, 2011). Food loss and waste (FLW) is a multi-faceted challenge with impacts on food security, rural livelihoods, resource use, and greenhouse gas emissions (related to the production of the food that is lost and emissions related to waste management). Accordingly, making progress in reducing food loss and waste is part of attaining the Sustainable Development Goals related to ending extreme poverty (SDG 1), ending hunger (SDG 2), achieving inclusive and sustainable growth (SDG 8), ensuring sustainable production and consumption (SDG 12, including the specific target to halve global per capita food waste (SDG target 12.3)), and last but not least to take urgent action to combat climate change and its impact (SDG 13) (Guo et al., 2020; United Nations, 2015). Within the food system and along food supply chains from production to consumption, GHG emissions aggregate as inputs and energy are required for production, consumption, processing, (refrigerated) storage and transportation, and other activities (FAO, 2017; Guo et al., 2020). This starts with production-phase GHG emissions (all emissions up to the farmgate), which comprise the majority of full-life GHG emissions – some 60% of total emissions for cereals and up to 90% of total emissions for meat (Porter et al., 2016). Leaving food that ends up being consumed as intended aside, food that is produced but lost or wasted somewhere along the chain thus contributes unnecessarily to an already problematic climate burden. In low and middle-income countries, losses early on in the chain tend to be predominant, whereas in developed economies food waste at the retail and consumer levels is a bigger issue (Hodges et al., 2011).

Especially losses in staple foods – which are one of the largest loss categories in terms of volume – negatively impact the food and nutrition security of vulnerable populations. For a large share of the world's population rice is a major staple food, including some of the poorest regions in Sub-Saharan Africa (CGIAR Research Program on Rice, 2013; Kok and Snel, 2019). In these regions, the majority of rice crops is grown on smallholder farms of only a few hectares. Previous research on food losses in Sub-Saharan Africa has focused predominantly on maize crops, while rice as a major staple food has been researched to a limited extent (Affognon et al., 2015; Kaminski and Christiaensen, 2014). More focus on rice is therefore warranted; not only because of its important role as a staple food in less developed regions, but also because losses in the rice chain account for some 10% of global FLW-induced Greenhouse Gas emissions (Guo et al., 2020).

Nigeria is the largest producer of rice in Africa, with approximately 90% of rice being produced by smallholder farms with limited resources (Erenstein et al., 2003; Ricepedia, 2012). In 2018, rice production in Nigeria was 5.8 million tons, with 3.2 million hectares under cultivation (KPMG, 2019). Rice exports are negligible, and production is predominantly for domestic consumption (FAO, 2020). Increasingly, this growing demand for rice has been fulfilled with growing import volumes.

The research on food loss in rice so far has predominantly focused on losses during storage, and ways to improve storage facilities so as to reduce losses (Affognon et al., 2015; Kumar and Kalita, 2017; Yusuf and He, 2011). However, harvesting and threshing activities have also been identified as critical loss points (Appiah et al., 2011; Food and Agriculture Organization of the United Nations (FAO), 2018; Kok and Snel, 2019), but so far with limited and ambiguous evidence on the magnitude of losses and the effectiveness of interventions. Fig. 1 below shows the on-farm product flow in a typical rice chain, with the range of loss figures per activity reported in literature indicated in parentheses.

We see that high losses are sometimes reported for the harvesting, threshing, winnowing, and storage stages, but with a wide range between the lowest and highest loss percentages found in the literature. Frequently, mechanization of harvesting and threshing activities is mentioned as a potentially loss-reducing intervention but has received little attention from research so far. Estimated losses for manual harvesting range from 1.6 to 12% (Alizadeh and Allameh, 2013; Bala et al., 2010; M. Gummert, 2013; Kok and Snel, 2019). Two studies researching the effect of mechanization as a loss-reducing intervention report losses of 3% for combine harvesting (M. Gummert, 2013) and 1.5% for the use of a reaper (Alizadeh and Allameh, 2013). Estimated losses in manual threshing range from 1.45 to 11% (Bala et al., 2010; Kok and Snel, 2019), and in mechanized threshing from 1.01% (Alizadeh and Allameh, 2013) to 3.15% (Selvi et al., 2002). Strikingly, Nath et al. (2016) find

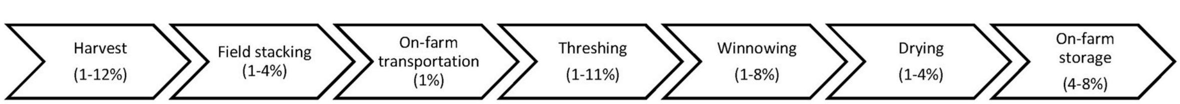

Fig. 1. On-farm activities in typical rice chain (range of loss estimates from literature in parentheses).
Note: Based on estimates from literature (Alizadeh and Allameh, 2013; Appiah et al., 2011; Bala et al., 2010; Martin Gummert, 2012; Jang et al., 2014; Kok and Snel, 2019; Kumar and Kalita, 2017; Nath et al., 2016; Selvi et al., 2002).

that mechanized threshing results in *greater* losses than manual threshing, but use a questionable baseline (FAO figures from 1986). In sum, the actual impact of mechanization on food losses in rice production is still uncertain, with a wide range of possible levels for all chain stages.

Related, also questions remain as to why mechanized farm equipment is used relatively little in Africa compared to other low- and middle income regions. Mechanization in agriculture has relatively recently come back into focus of policymakers and researchers (Daum and Birner, 2020), spurred by the observation that while mechanization has been successful in Asia (Hegazy et al., 2013), the experience in Sub-Saharan Africa has been characterized by low levels of adoption and high levels of abandonment of postharvest loss-reducing interventions, including mechanized systems (Sims and Kienzle, 2006; World Bank, 2011). Suggested reasons for this trend in Sub-Saharan Africa include lack of accessibility and financial sustainability for smallholder farmers, low cultural acceptability, and supporting policies with timeframes that are too short for sustained impact (World Bank, 2011). A meta-analysis on food losses in Sub-Saharan Africa (Affognon et al., 2015) presents evidence (though sparse) that high initial costs, low effectiveness, lack of markets, and poor scalability impede adoption and sustained impact. The insight remains limited however, as only 15% of studies addressing loss-reducing interventions include a cost-benefit analysis. Overall, there is very limited evidence on the impact and effectiveness of post-harvest loss-reducing interventions (Sheahan and Barrett, 2017). A recent overview of agricultural mechanization in Africa (Daum and Birner, 2020) shows that research findings are still ambiguous on several major questions regarding mechanization, citing mixed evidence on the relationship between mechanization and socioeconomic development (including rural (un)employment and gender disparities), and ambiguity on the ability of mechanization to increase yields. Moreover, the same overview highlights the current uncertainty around the question of environmental impact of mechanization, and whether this would lead to a net increase or decrease of GHG emissions (Daum and Birner, 2020; Searchinger et al., 2015).

The uncertainty on these issues may partly be attributed to the limited suitability of mechanized farm equipment (especially imported from abroad) for smallholder farms in Sub-Saharan Africa (Hegazy et al., 2013). Also the limited quality of machinery (Appiah et al., 2011), lack of service providers and lack of training of operators (Food and Agriculture Organization of the United Nations (FAO), 2018) have been cited as factors impeding effectiveness. To effectively evaluate the impact of mechanization as such, its impact should be isolated from other factors that influence its attractiveness or effectiveness – i.e. experiment with manual and mechanical practices under otherwise identical conditions. Nevertheless, those factors that are mentioned to explain lack of adoption highlight the importance of the appropriateness of the intervention in a food system context and the relevance of taking a broad perspective when investigating an intervention's success – or lack thereof. For sustained adoption and impact it needs to be appropriate for smallholder farms (Sims and Kienzle, 2016), and be available, accessible, and effective in producing direct (financial) benefits for farmers (Hodges et al., 2011), but also fit in the context of the local food system with its specific socioeconomic, environmental, and industrial conditions (Hegazy et al., 2013). Based on this insight, recent research has placed increasing emphasis on mechanization not only as a way to improve productivity and product quality, but also with attention to socioeconomic and sustainability dimensions (Fischer et al., 2018; Houmy et al., 2013) and within the context of sustainable and inclusive development of the food system (Sims et al., 2016). As mechanization reduces labor requirements, this may lead to increased unemployment, but may also mitigate problems due to labor scarcity (Houmy et al., 2013; Park et al., 2018; Saliou et al., 2020). The labor-saving nature of mechanical equipment can also have positive socio-economic effects such as children being able to spend more time in school, and adults having opportunities to earn more income in other activities (Ali et al., 2018; Hodges et al., 2011). However, these opportunities need to be available and accessible in the region. There is very little and overall mixed evidence on the impact that mechanization has on gender relations. Hegazy et al. (2013) discuss the risk that men are more likely to operate mechanized equipment at the cost of women's incomes – which is supported by evidence that women in Sub-Saharan Africa seem to have less access to mechanized equipment (Fischer et al., 2018). Other research contradicts these claims, reporting that women are more likely than men to use mechanization (Saliou et al., 2020), are more involved in rice production when improved production technologies are implemented (Addison et al., 2020), and that female-headed households are more likely to implement loss-reducing interventions and report overall lower losses (Kaminski and Christiaensen, 2014). Regarding the environmental impact of mechanization, Hegazy et al. (2013) mention increased GHG emissions as a risky side-effect. However, research in this domain is very limited, and the trade-off between emissions from equipment and potentially avoided FLW-induced GHG emissions has not been investigated yet. In sum, some of the most important questions regarding agricultural mechanization in Sub-Saharan Africa still deserve further attention (Daum and Birner, 2020).

Therefore, we conduct a controlled experiment with mechanization of harvesting and threshing activities at smallholder rice farms in Nasarawa, Nigeria. Such a setup is warranted for several reasons as also discussed above. First of all, evidence on one of the most important outcomes of mechanization – effectiveness in increasing rice yields and reducing losses – is still ambiguous (Daum and Birner, 2020). Secondly, while a large share of research so far has relied on surveys to estimate losses and the impact of different interventions, surveys have the risk of *under*estimation of losses by farmers (Kaminski and Christiaensen, 2014; Kok and Snel, 2019). A problem for researchers is therefore that the effectiveness of interventions may not be effectively evaluated, and in practice adoption of loss-reducing interventions may be limited when farmers are not (made) aware of impact reduction of losses may have on their operation and income. A controlled experimental setup can address this problem and more accurately isolate and evaluate the impact of an intervention. Third, a comprehensive impact evaluation entails a wider variety of food system outcomes than is commonly addressed in research – including implications for farmers' incomes, food losses, environmental footprint, and socioeconomic effects. The section below details how this is addressed through a controlled experiment.

3. Data and method

For the purpose of this study, we follow the definition of food loss in the rice chain as formulated by Kok and Snel (Kok and Snel, 2019) who performed a study in a similar context, namely as "Mature rice that is ready for harvest but not ending up for human consumption." The latter part of this definition – ending up for human consumption – is later operationalized as the share of the mature grown rice that is successfully harvested, threshed, and collected to bring to the market.

We conducted two experiments. One to investigate the effect of switching from manual rice harvesting to mechanized rice harvesting, holding everything else (including the threshing method, which was mechanical) constant. The second experiment investigated the effect of switching from manual rice threshing to mechanized threshing, holding everything else (including the rice being manually harvested) constant.

The impact on food loss, farmer income, and GHG emissions of switching from manual to mechanical harvesting and threshing is investigated using a controlled experimental setup. Five standard smallholder farms were selected from the same region, Nasarawa State in North Central Nigeria. All five farms are involved in the Rice Outgrowers Initiative of Olam International (a major international agri-food company with approximately 66,000 farmers in rice, of which 32,800 rice outgrowers in Nigeria), and are part of the same outgrower program, through which they received similar guidance and instructions. The farms are of similar plot sizes (approximately 5 ha). The same rice cultivar (Faro44) and harvesting and threshing machinery were used in all experiments.

The measurements were all conducted by field experts from Olam International in November 2020, following detailed instructions and using measurement templates developed by this paper's authors. These instructions (Appendix A for harvest, Appendix C for threshing), and detailed template to record measurements (Appendix B for harvest, Appendix D for threshing) are included as appendices to this paper. The field experts used one scale and one moisture meter for measurements on each farm, calibrated before every measurement. Moreover, additional pictures were taken on the farms, and field experts were debriefed extensively about any other observations they made during the measurement cycles.

Three measurements were conducted at each farm, for a total of fifteen measurement cycles per experiment. The next sections outline the step by step process followed to research the impact of mechanized harvesting and mechanized threshing, respectively.

3.1. Measuring losses in harvest

At each farm, two plots of 24 m^2 were randomly selected, aimed to have the same dimensions and close to each other, to ensure that there were no differences between the plots other than the method of harvesting. The plots were also selected to be located at the same distance from threshing location. This distance varied between 20 and 42 m, with an average distance of 33m, over which bundles of rice were transported by foot after field drying.

One of these plots was designated for manual harvesting (the usual practice), and the other plot was harvested mechanically. Fig. 2 below shows how these two methods work in practice.

Directly after harvest, the following was recorded for both plots:

- The weight of total harvested material (plant + paddy)
- Average moisture content of 3 samples of paddy.

Two 6 m^2 subsections of both plots were selected. From each 6 m^2 subsection, the paddy was picked up from the ground, and its weight recorded. The two samples were labeled Sample 1 from the manually harvested plot and Sample 2 from mechanically harvested plot.

After drying (as usual), the following was recorded for both 24 m^2 plots:

- The drying time and weather during the drying.
- Average moisture content of 3 samples of paddy.

Subsequently, Sample 1 and Sample 2 were transported to the threshing location. At threshing location the following was recorded:

- Weight of total dried plant material and paddy
- Distance and transportation mode between drying and threshing locations
- Weight of paddy successfully threshed (both samples with mechanical threshing).

At every farm, this cycle was repeated three times, each time with different plots but the same procedure.

After completion of the measurement, it was verified that drying time (3 days of drying) and weather during drying (no rainfall during drying time in all measurements) were constant across all measurements, and there were no outlier observations in terms of distance from the threshing location.

3.2. Measuring losses in threshing

For threshing a similar procedure was followed. Two plots of 24 m^2 were selected randomly, aiming to have the same dimensions and be located close to each other, at the same distance from threshing location. The plots were harvested (manually) as usual, by the same person, and the paddy was left to dry in the field as usual for the same number of days (3).

After harvesting, the following was recorded:

- Drying time (3 days)
- Weather during drying time (no rainfall during drying time for all measurements)

The samples from the plots were then moved to the threshing location, Sample 1 to be threshed manually, Sample 2 to be threshed mechanically. Fig. 3 below shows how the two different methods work in practice.

At the threshing location, the following was recorded:

- Weight of total dried plant material and paddy for both samples
- Distance and transportation mode between drying and threshing locations
- Weight of grains threshed successfully for both samples.

As with the harvesting experiment described above, this cycle was repeated three times, each time with different plots but the same procedure. Also, here, it was verified that the drying time (3 days of drying) and weather during drying (no rain showers) were constant, and that all plots were at comparable distance from the threshing location.

4. Results

We conducted two experiments. One to investigate the effect of switching from manual rice harvesting to mechanized rice harvesting, holding everything else (including the threshing method, which was mechanical) constant. The second experiment investigated the effect of switching from manual rice threshing to mechanized threshing, holding everything else (including the rice being manually harvested) constant.

Fig. 2. Manual and mechanical harvesting practices
Source: Photographs taken by Olam's field experts during experiment in Nasarawa, Nigeria (November 2020).

A) Manual threshing B) Mechanical threshing

Fig. 3. Manual and mechanical threshing practices
Source: Photographs taken by Olam field experts during experiment in Nasarawa, Nigeria (November 2020).

Both experiments – switching to mechanized harvesting and switching to mechanized threshing – yielded data on mechanical and manual practices. First we compare product losses, followed by a business case analysis juxtaposing the yield differences with cost differences between different technology scenarios, as well as a comparison of the GHG emissions per kg rice available for consumption.

4.1. *Impact of mechanization on losses*

In the experiment with manual versus mechanical harvesting, on average a larger amount of plant material (including paddy) was harvested from the plots that were harvested mechanically compared to the plots that were harvested manually (on average 22.99 kg versus 22.18 kg per experimental plot). Moreover, the loss of paddy on the field during harvesting was lower for mechanical harvesting (0.93%) than for manual harvesting (2.38%). The threshing result (the paddy yield after mechanical threshing) was slightly higher for the samples that were harvested mechanically, with a slightly higher threshing efficiency (defined as the percentage of the dried plant material (holding the paddy) that is threshed as paddy). See Table 1 for a summary of the results.

When comparing manual and mechanical threshing (see Table 2), we find that mechanical threshing is slightly more efficient than manual threshing – the paddy yield after mechanical threshing equals 33.1% of the dried plant material (holding the paddy), whereas for manual threshing this ratio is 31.1% - a 6.5% efficiency difference. Unfortunately, the measurements of threshing losses (described as optional in the measurement protocol) did not yield enough information to draw conclusions on the absolute value of threshing losses. To estimate the threshing losses, one could use the following workaround: assume a 1% threshing loss for mechanical threshing, approximating estimates of losses during mechanical threshing from literature (Alizadeh and Allameh, 2013; Hodges et al., 2011; Nath et al., 2016; Selvi et al., 2002). Subsequently, by calculating from the differences in yield (and assuming that the samples were as good as identical after harvest, from similar plots, with similar harvesting efficiency – safeguarded by the plots being close together, and harvested in the same way by the same person), we find an average threshing loss of 7% for manual threshing. In conclusion, also for threshing, mechanized practices produce a higher yield and lead to reduced losses. However, to calculate the difference between the scenarios these absolute values are not necessary, and to avoid weakening the results, we will not use these assumptions.

When combining the information obtained from the two experiments and extrapolating these findings from the 24 m^2 plots to 1 ha, we find differences in yield for different combinations of technologies as shown in Table 3.

Switching from manual to mechanized threshing improves the overall yield (all else being equal) by 6.5%, compared to the baseline scenario of manual harvesting and manual threshing. Implementing both mechanized harvesting and threshing increases the yield per hectare by 16.6%.

Table 1
Average harvesting and threshing results of manual versus mechanical harvesting (per plot of 24 m^2, standard deviation in parentheses).

	Manual harvesting	Mechanical harvesting
Harvested material and paddy after drying, before threshing (kg)	22.18 (1.58)*	22.99 (1.49)
Loss of paddy on land during harvesting (%)	9.55%	0.93%
Paddy yield after mechanical threshing (kg)	6.94 (0.55)**	7.58 (0.59)
Threshing efficiency (mechanical)	32.1%	32.9%

* Average of three series of measurements; one from the harvesting experiment, and two from the threshing experiment, in which the threshing method varied, but the harvesting method (manual) was held constant.
** Average of two series of measurements; one from the harvesting experiment, and one from the threshing experiment, in which the harvesting (manual) and threshing (mechanical) were the same.

Table 2
Differences in threshing efficiency and losses between manual and mechanical threshing.

	Manual threshing	Mechanical threshing
Threshing efficiency	31.1%	33.1%

Table 3
Paddy yield in kg per hectare for different combinations of technology.

		Threshing	
		Manual	Mechanized
Harvesting	Manual	2789	2967
	Mechanized	3054*	3257

* Imputed.

4.2. *Business case*

Above it is shown that switching from manual to mechanical practices in rice production produces considerable increases in yield. In this section we consider what the business case for this switch looks like for smallholder farmers, and whether the costs of mechanization are sufficiently offset by the benefits. To do so, and to make the results more insightful for practice, we express the quantitative findings described above as the impact on costs and revenues per hectare. To estimate the impact that mechanization may have on a larger scale, we also extrapolate the findings of the pilot study to 700 farmers (Olam pilot farmers group), all rice farmers in Nigeria contracted by Olam (32,800 farmers), and the entire rice production area in Nigeria (3.2mln ha). For this extrapolation, we use the assumption that the average smallholder farm connected to Olam comprises 1.92ha, as Kok and Snel (2019) found in a large scale survey with Olam rice farmers in Nasarawa in Nigeria.

Table 4
Results per harvest of switching to mechanized harvesting and/or threshing.

Impact	Switching to mechanized harvesting		Switching to mechanized threshing		Switching to mechanized threshing and mechanized harvesting	
	Loss reduction (kg)*	Profit increase (N)	Loss reduction (kg)	Profit increase (N)	Loss reduction (kg)	Profit increase (N)
Per ha	299 kg	50,531	180 kg	30,420	479 kg	80,555
Per farmer Olam	575 kg	88,404	346 kg	24,674	921 kg	155,650
Pilot Olam (700 farmers)	402 ton	68 mln	242 ton	41 mln	645 ton	109 mln
Olam farmers Nigeria (32,800)	18.8 kton	3.2 bln	11.4 kton	1.9 bln	30.2 kton	5.1 bln
All rice farmers Nigeria (3.2mln ha)	957 kton	162 bln	576 kton	97 bln	1533 kton	259 bln

* of Paddy, directly after harvest, before drying.

Table 4 below shows the loss reductions that can be achieved with different technologies, and the financial savings farmers incur as a result. We assume a farmgate rice price of N169 (Nigerian Naira) per kilogram, as it was at the moment of the experiment (at that moment with an exchange rate of approximately 400 Naira to one US Dollar).

For a comprehensive business case evaluation, these increases in yield (and hence profitability) should be weighed against the costs incurred for mechanizing farm operations previously performed with manual labor. For these calculations, we use the assumptions listed in Table 5 below, provided by the field experts who conducted the pilot studies in Nasarawa (or other secondary sources, indicated where appropriate). If a range of plausible values was indicated, the average was used for this calculation (e.g. experts estimated the cost of renting a reaper between 15,000 Naira and 20,000 Naira per hectare of farmland, so the average of N17,500 per hectare was used). For ease of comparison, we calculate this business case per ha.

From the analysis above, we take the rough estimate that to obtain a certain amount of rice paddy, approximately three times as much dried plant material (containing the paddy) needs to be threshed. Moreover, we assume that when using mechanized farm equipment, this needs to be operated by two people, hence incurring the labor cost of these two people for the duration of use of the machinery – the validity of this estimate was confirmed by the field experts conducting the experiment. The business case scenarios are based on the technology used and the average yield per hectare from the study measurements. Taking Scenario 0 (all manual practices) as the baseline scenario, the revenue increases

Table 5
Business case parameters.

Parameter	Value
Labor costs (N per hour)	125
Rice price (N per kg paddy)	169
Fuel price (N per liter)	165.7[a]
Harvesting labor needed (hours per ha)	160
Threshing labor needed (hours per ha)	80
Cost of renting reaper (model 4 GL-120) (N per ha)	17,500
Cost of buying reaper (N)	820,000
Reaper fuel consumption (liters per ha)	4.5
Reaper capacity (ha per day)	1
Cost of renting thresher (model Sh 101–2) (N per ha)	10,000
Cost of buying thresher (N)	350,000
Thresher fuel consumption (liters per ha)	5.5
Thresher capacity (metric ton of input (dried plant material) per hour)	1

[a] GlobalPetrolPrices.com (2021), accessed 16-2-2021.

Table 6
Business case for switching from manual to mechanical harvesting and/or threshing.

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Harvesting	Manual	Mechanized	Manual	Mechanized
Threshing	Manual	Manual	Mechanized	Mechanized
Average yield (kg paddy per ha)	2786	3054	2967	3257
Revenue (N per ha)	470,823	516,126	501,423	550,433
Harvesting costs (N per ha)	20,000	20,246	20,000	20,246
Threshing costs (N per ha)	10,000	10,000	13,161	13,536
Revenue increase (N per ha)		45,303	30,589	79,599
Cost increase (N per ha)		246	3161	3782
Financial result (N per ha)		**+45,057**	**+ 27,428**	**+ 75,871**
Financial result (%)		**+9.5%**	**+ 5.8 %**	**+ 16.1 %**
Labor saved (hours per ha)		144 in harvesting	62 in threshing	144 in harvesting, 59 in threshing

and the cost increases look as shown below in Table 6. It should be noted here that this only entails a comparison of the harvesting costs relative to the total revenue from rice, and that we assume pre-harvest inputs and labor costs to be constant.

Here we see that the increased revenue from the increased yield from 1 ha of rice due to the introduction of mechanized farm equipment by far outweighs the cost increase of using a mechanized reaper and thresher. Switching to mechanized threshing increases the profit of a farmer per ha (all else equal) by 27 kNaira (approximately $68), and switching to mechanized harvesting and threshing increases a farmer's profit by 76 kNaira (approximately $190) – a clearly positive business case when assuming that the only change the farmer makes is using mechanized harvesting and threshing instead of manual labor when the rice is mature. The positive business case is also robust to the introduction of any plausible number of additional workers (at N125 per hour) for extra help, transportation, and other miscellaneous activities around the mechanized harvesting and/or threshing. Mechanized threshing is more expensive than manual threshing (the cost of renting the thresher alone is equal to the total labor costs of manual threshing), but the improved

Table 7
Equipment cost comparison between buying and renting reaper and thresher (for individual farmer in cooperative).

	1 harvest	2 harvests	3 harvests	4 harvests	5 harvests
Cost of renting (N per harvest per farmer)	27,500	27,500	27,500	27,500	27,500
Cost of buying (N per harvest per farmer)	78,000	29,000	26,000	19,500	15,600

threshing efficiency and reduced losses of the threshing machine increase the total yield by far enough to make this intervention worthwhile. Even more striking, switching from manual harvesting to mechanized harvesting does not increase the cost of harvesting significantly, but the higher amount of material harvested and ultimately the higher amount of paddy yielded after threshing increase considerably.

Also, for farmer cooperatives there is a business case here. A reaper can harvest 1 ha per day, and – with a seasonal time window of some 35 days in which rice can be harvested – about 30 ha per season can be harvested with one machine, accounting for some downtime and maintenance. As a thresher has the capacity to thresh the material from 1 ha in approximately one day, also a thresher can service some 30 ha per season. Assuming that the average smallholder farmer has approximately 2 ha of rice under cultivation, 15 farmers could share the equipment for a season if they buy it together. With a reaper costing N820,000 to buy and a thresher N350,000, the upfront cost for a single farmer with 2 ha in a 15-farmer cooperative would be N78,000. We assume everything other than the rent versus buy decision to be equal, including the revenue increase, operating costs, interest rate and maintenance. This is supported by the field staff's estimations that the cost of training and setting up farmer based organizations is negligible.

The field experts conducting the experiment confirmed that the machinery is expected to have a lifespan of at least five years, and up to eight years and longer if it is maintained well. The comparison of the equipment cost in the renting and buying scenarios (Table 7) shows that if the cost of buying the equipment with a cooperative of 15 farmers can be spread over 3 harvests or more, buying becomes the more cost-effective option. Knowing that in the long run buying equipment is more economical, the most important limiting factors are likely the capacity of farmer cooperatives to procure, maintain and store the equipment, and ability of individual farmers to co-invest and cover the higher upfront cost of buying equipment.

4.3. Greenhouse gas emissions

In the experiments and scenarios above, the introduction of machinery helped to reduce food losses in rice production and provided a positive business case for smallholder farmers to improve their livelihood. For a complete assessment of the impact of mechanization in rice production, we also consider the GHG emissions in several scenarios. The Agro-Chain Greenhouse Gas Emissions (ACE) calculator (Broeze, 2019) allows us to calculate Food Loss and Waste-induced Greenhouse Gas emissions from the rice that is grown, but lost before consumption – as well as the emissions that can be avoided when losses of rice are reduced through the introduction of mechanized harvesting and threshing on smallholder farms. Using the assumptions above, and assuming 1% threshing losses for mechanical threshing (see section 3.1) and typical crop GHG emission factor 3.66 kg CO_2-eq. per kg paddy rice (derived from Porter et al., 2016, adapted to paddy:white rice ratio), and fuel use as given in Table 5, we find the following GHG emissions, net of emissions from equipment (Table 8).

If all rice farms in Nigeria were to mechanize harvesting and threshing operations, the net effect would be 5.4 Mton CO_2-eq. of greenhouse gas emissions avoided (all else equal) – roughly similar to

Table 8
Climate impact of mechanization in rice production.

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Total paddy rice growth (kg/ha)	3315	3315	3315	3315
Harvesting method	Manual	Mechanized	Manual	Mechanized
Losses in harvest	9.55%	0.93%	9.55%	0.93%
Threshing method	Manual	Manual	Mechanized	mechanized
Losses in threshing	7%	7%	1%	1%
Total paddy threshed rice (kg/ha)	2786	3054	2967	32757
GHG emissions per kg produced paddy rice (kg CO_2-eq. per kg threshed rice) (assuming crop GHG emission factor 3.66 kg CO_2-eq. per kg paddy, see text above)	4.352	3.979	4.096	3.744
Climate impact of mechanization (emissions avoided, kg CO_2-eq)				
Per ha (kg CO_2-eq.)		1,042	716	1,696
Per farmer (1.92ha) (kg CO_2-eq.)		2000	1,374	3,256
Rice farms in Nigeria (3.2mln ha) (Mton CO_2-eq.)		3.3	2.3	5.4

the annual GHG emissions of a country such as Burundi (World Bank, 2021). This is a considerable net positive climate impact of mechanizing production of one crop in one country that, as shown above, can also go hand in hand with improvements in farmers' livelihoods.

4.4. Socio-economic observations

In addition to the findings from the experiment, we also debriefed the field experts conducting the experiments on their observations on socio-economic aspects, such as the division of labor and mix of activities performed by different people in the community. Aside from conducting the experiment on five farms, they have also been involved in introducing mechanized farm equipment on some 700 farms part of Olam International's Rice Outgrowers Initiative. These farmers are stimulated and facilitated to buy the equipment as part of farmer cooperatives, and youth from the farmer households are trained to operate the machinery.

Overall, the experts observe that the switch to mechanical harvesting and threshing is well received. In Nasarawa, rice cultivation is predominantly the task of women (except for more physical tasks such as bagging and loading), and they now save time otherwise spent on (rather tedious) threshing and winnowing. The time saved is spent in a variety of ways, such as working in warehouses and quality assurance and cultivation of other crops, but also on social and family matters. Also, since there is usually no shortage of uncultivated land, smallholders that switch to mechanized harvesting and threshing often expand their farm by one or 2 ha since managing the farmland becomes easier. Overall, farm output and family incomes increase.

The focus within the Rice Outgrowers Initiative on farmer cooperatives is rather new. A previous push for mechanization in Nigeria in the 2000s was implemented top-down by the national government, but was highly politicized and as a result most (imported) machinery disappeared. In the current initiative, the cooperatives buy the equipment outright and charge a use fee for members, and a slightly higher fee for others outside the cooperative who want to use the equipment. The main barrier seems to be the upfront investment for buying the equipment, therefore assistance to obtain financing is often necessary.

A risk often mentioned in literature on mechanization, namely it causing rural unemployment, is generally not observed in Nasarawa. During the harvest there is usually a shortage of labor, since rice and other crops need to be harvested at the same time. Also, in areas where the mechanization effort has been ongoing for a few years new forms of entrepreneurship have appeared in the form of small machine workshops that offer spare parts and maintenance and repair services. The local youth that is specifically trained to operate and maintain the machinery also sees expanded opportunities in working not only on the family farm, but offering mechanized reaping and threshing services as contractors to other farmers who don't have the experience with machinery. Some of the more experienced operators have noted that the equipment (imported from China) seemed on the big and heavy side to work the small farms, presenting an opportunity for adaptation or even local manufacturing of machinery suited to local needs.

5. Discussion of results

This experiment showed that replacing manual labor in rice harvesting and threshing with machinery increases the amount of paddy yield per hectare on average by some 16.6% and reduces loss-induced greenhouse gas emissions (per kg of paddy) considerably. It also constitutes a positive business case for the farmer with a revenue increase of (on average) 80 kNaira per hectare at a cost increase in harvesting and threshing of only N3782, in case the farmer rents the equipment. If a group of farmers cooperatively buys the equipment it is even more economical in the long run, with cooperatively buying becoming more cost-effective than renting after 2 harvests. Last, switching to mechanized equipment reduces food loss-induced GHG emissions by far more than the additional emissions from the machinery. This work clears up the most important open question regarding mechanization, as discussed in the introduction of this paper, namely that mechanization is effective in increasing yield in a climate-positive way, while also producing a net financial benefit for farmers. This supports the longer-established idea that mechanization should be part of any agricultural development strategy in less developed countries (Hegazy et al., 2013), and that policy should stimulate the appropriate level and type of mechanization to be available and accessible to smallholder farmers.

Also some notes on limitations of this study are in order. First of all, we did not account for the role of agricultural inputs. This does affect yield and losses, and the farmer's bottom lines, but was not part of this analysis. We expect however, that the results are relatively (percentagewise) in line with this research for e.g., other varieties. In particular, in case of the contract farmers of Olam the inputs of the production system will not differ that much. Secondly, there are other ways to evaluate interventions' success. Can finance be arranged for smallholders to rent or buy the equipment, is technical support and training available, or do social aspects play a role when a group of farmers wants to rent these machines (e.g., planning)? These qualitative aspects are not considered in this study.

These lacunae in the scope of this study, as well as the contributions this study has made, also inform the recommendations we can make for further research. First, this study has shown the value of controlled experimental research on loss-reducing interventions in food systems, and the value of a comprehensive analysis, covering not only effectiveness, but also economic feasibility and environmental sustainability, including trade-offs of interventions. Further research can broaden this approach to other regions, interventions, and products. Secondly, while this study has shown the impact of mechanization, a worthwhile next step would be to weigh different loss-reducing interventions against each other. Smallholder farmers have limited resources and cannot implement all conceivable improvements at once, so therefore more fine-grained guidance on which investment would produce the best return – given the farmer's context and resources – is desirable. Third, the scope and timeframe of this study was tuned to a quantitative comparison between manual and mechanized harvesting and threshing, with respect to relevant indicators. An interesting question for future research to pursue is if and how (based on these positive results) exactly the adoption of improved practices proceeds, what the most important driving factors are, who can play what role and how it affects food systems in the long run. Fourth, this study has shown the attractive business case of mechanized systems, while earlier research has pointed to the low uptake of these systems in the African context. This study discussed examples of renting equipment and farmer cooperatives as means to improve accessibility for smallholder farmers. A more comprehensive investigation of different organizational forms to improve the accessibility of mechanized systems – and the associated business cases – is another worthwhile venue for future research.

6. Conclusions and policy implications

The most essential insight to be gained from this study is that mechanization in rice production works to increase yields, improve farmers' incomes, and that this can be a climate-positive improvement. This result juxtaposed with the observation that mechanization is the exception rather than the rule in Sub-Saharan African rice production shows that there are considerable barriers to mechanization to be addressed. Our findings showed the relatively high upfront cost of renting (let alone buying) equipment, which may be prohibitive for farmers to start with mechanization at all. This identifies the main voids for market actors and policymakers to address, namely lack of access to productivity-enhancing technology and a lack of access to credit that would make it possible to cover the upfront cost. In the context of the potential benefits we show to be had, it is important that stimulating the uptake of loss-reducing interventions and supporting the right enabling environment should be key parts of sustainable agricultural development strategies. From this insight we derive our other recommendations for policy.

First the imperative to increase the awareness, availability, and access to mechanized farm equipment. This can be implemented through a variety of organizational forms, such as renting equipment, but also for example through contractors, cooperatives and other models. The business case example evaluated in this study shows that renting equipment constitutes a relatively small up-front investment (especially for harvesting a nearly negligible cost increase over hiring labor), and produces immediate benefit in form of greater yield. On the other hand, purchase costs of modern machinery are prohibitive to uptake (820,000 Naira for buying a reaper, 350,000 Naira for buying a thresher). If the market for renting or other low-barrier access is not there, this should be stimulated, ideally in parallel with improving access to buying equipment through financing options. If this market is absent, farmers may be limited to buying older, second-hand equipment, running the risk that the low-quality equipment does not bring the full potential benefit of mechanization. Alternatively, policymakers can consider assisting farmer cooperatives to buy farm equipment for (paid) use by their members.

This extends to the second recommendation, namely to stimulate uptake. We have shown that mechanization produces immediate revenue increases for a relatively small up-front cost increase, but farmers need to be incentivized to make this up-front investment. This could be achieved through more demonstrations, education on efficient practices and technology, and subsidizing mechanization in early stages. As discussed above, this could be through stimulating a market for rental equipment, or supporting farmer cooperatives in buying equipment themselves.

Third is the recommendation to build technical know-how and capabilities. Primarily in rural communities, where lack of know-how is often mentioned as a reason for lack of adoption and abandonment of innovations. Moreover, the skill level of equipment operators determines the extent to which the potential loss reductions can be realized. This study shows that the balance between costs and returns strongly favors the proposed mechanized practices, but this should be stimulated with technical assistance, and access to technical know-how should be ensured for a persistent effect. Aside from specific rural communities, also on a larger scale growing demand for mechanized farm equipment can stimulate the development of local manufacturing and technical services sectors. The private sector in Nigeria already has examples of agricultural input suppliers training local farmers to do sales, assisting with financing, and providing extension services. Effective policy stimulating both the demand (increased uptake) and supply (equipment and technical capabilities) side of the market for mechanized farm equipment can trigger the development of similar reinforcing networks with complementary activities. An example of the virtuous cycle this can create is how mechanization of harvesting in Southeast Asia incentivized additional harvesting, and generated demand for more efficient (locally developed) drying technology.

Fourth, we recommend efforts to support lasting positive impact in the food system in general, and to prevent the premature abandonment of improved practices due to misalignment with the local context. Essential here is the idea that new practices are only sustainable when they are beneficial to all stakeholders in the food system. This starts with giving farmers access to mechanization, but also supporting access to markets and financing, and extends to continuing education and training. Mechanized harvesting and threshing are labor-saving innovations, which can be both positive (freeing up time for other activities, such as education and diversification to other sources of income) and/or negative (creating unemployment). The latter can only be counteracted with stimulation of the former, and appropriate policy focusing on rural development in the context of agricultural development can swing this balance to the positive side. The essence of these policy recommendations also extends to the private sector, development practitioners, and social impact investors. Switching to mechanized rice production reduces losses and GHG emissions, and improves farmers' livelihoods. Access to financing is a major barrier to the uptake of mechanized practices, but also an opportunity that should be responded to. Procuring equipment through farmer cooperatives can lower this barrier by reducing the upfront cost for farmers, and reduce the risk investors are exposed to by the possible default of a single farmer. Helping overcome this hurdle can be an impetus for further mechanization, and thus contribute to sustainable development with improved incomes, improved food security, reduced food losses, and reduced GHG emissions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Instructions to field experts, harvest measurements

Step-by-step measurement approach - Rice Olam Nigeria

Harvesting

General:

- Select 5 farmers from a selected region
- Carry out 3 measurements per farmer
- Use 1 scale for all measurements per farmer, and make sure you calibrate the scale before every measurement
- Use 1 moisture meter for all measurements per farmer, and make sure you calibrate it before every measurement
- Please make pictures of the data collection process when possible.

Per farmer:

o 1–2 pictures for manual harvesting
o 1–2 pictures for mechanical harvesting
o 1–2 pictures for drying process
o 1–2 pictures for transport to threshing location
o 1–2 pictures for threshing

Harvest start.

- Visit a farmer and select two plots of 24 m^2 randomly.
  o Preferably the selected plots have the same length and width (e.g. 24 m long/1 m deep, or 12 m long/2 m deep, or 8 m long/3 m deep).
  o Preferably the selected plots are near each other, so that the distance to the threshing place is almost equal for both plots.
  o One plot is for manual harvesting, one plot is for mechanical harvesting.

- Harvest 1 plot of 24 m^2 manually as usual.

- Harvest 1 plot of 24 m^2 by machinery.

1. Weigh the total harvested plant material + paddy. Do this for sample 1 (manually harvested plot) and sample 2 (mechanical harvest plot) (Table 1).
   - o Do the weighing process in several separated bundles that are easy to gather.
   - o Move the weighing scale as close as possible to every bundle.
   - o Make sure you calibrate the scale before every measurement.
   - o When the bundles do not easily fit the weighing scale, please stand on the weighing scale with the bundles of harvested plant + paddy. Take off your own weight from the total weight

2. Measure the moisture content of the paddy (Table 2).
   - o Use the average of 3 separate measurements like usual
   - o Make sure you calibrate the moisture content meter before use

- Per harvested plot, select a part of 6 m^2

- Pick up de paddy from the ground from this 6 m^2 part

3. Weigh the paddy picked from the ground. Do this for sample 1 (manually harvested plot) and sample 2 (mechanical harvest plot) (Table 3).
   - o Make sure you calibrate the scale before every measurement.

- Leave both harvested plots in the field to dry as usual.
   - o Leave it for 3–4 days, depending on the strength of the sun.
   - o At least make sure you dry both harvested plots for the same amount of days.

Harvest continuation after 3–4 days.

4. Write down (Table 4):
   a. How many days did you dry the paddy?
   b. On how many days of this drying period a rain shower took place?

5. After drying, measure the moisture content of the paddy (Table 5).
   - o Use the average of 3 separate measurements like usual
   - o Make sure you calibrate the moisture content meter before use

- Move sample 1 (manually harvested) to the threshing location.

6. Weigh the total dried plant material + paddy of sample 1 (manually harvested) (Table 6).
   - o Do the weighing process in several separated bundles that are easy to gather.
   - o Place the weighing scale on top of the tarpaulin.
   - o Make sure you calibrate the scale before every measurement.
   - o When the bundles do not easily fit the weighing scale, please stand on the weighing scale with the bundles of harvested plant + paddy. Take off your own weight from the total weight

7. Write down (Table 7):
   a. What is the distance between the drying place and threshing location?
   b. How did you move the bundles? E.g. walking, by cart, by car.

- Start threshing sample 1, preferably with the mechanical thresher

8. Weigh the paddy that is successfully threshed for sample 1 (Table 8).
   - o Make sure you calibrate the scale before every measurement.

- Move sample 2 (mechanical harvested) to the threshing location.

9. Weigh the total dried plant material + paddy of sample 2 (mechanical harvested) (Table 6).
   - o Do the weighing process in several separated bundles that are easy to gather.
   - o Place the weighing scale on top of the tarpaulin.
   - o Make sure you calibrate the scale before every measurement.
   - o When the bundles do not easily fit the weighing scale, please stand on the weighing scale with the bundles of harvested plant + paddy. Take off your own weight from the total weight

- Start threshing sample 2, preferably with the mechanical thresher.
   - o Make sure you thresh both samples at the same way (preferably mechanical, otherwise both manually)

10. Weigh the paddy that is successfully threshed for sample 2 (Table 8).
    o Make sure you calibrate the scale before every measurement.

- Repeat this exercise for this farmer, so in total you should have applied this measurement methodology for harvesting 3 times per farmer.

- Repeat this exercise for 5 farmers in total.

Appendix B. Measurement template, harvest measurements

Table 1

	Weight total harvested plot	Unit
Sample 1 (manually)		kg
Sample 2 (mechanical)		kg

Table 2

	Moisture content paddy after harvesting	Unit
Sample 1 (manually)		%
Sample 2 (mechanical)		%

Table 3

	Weight from paddy from ground from $6m^2$	Unit
Sample 1 (manually)		kg
Sample 2 (mechanical)		kg

Table 4

	Drying days and rain showers	unit
a. How many days did you dry the paddy?		days
b. On how many days of this drying period a rain shower took place?		days

Table 5

	Moisture content paddy after drying	Unit
Sample 1 (manually)		%
Sample 2 (mechanical)		%

Table 6

	Weight total dried sample plant material + paddy	Unit
Sample 1 (manually)		Kg
Sample 2 (mechanical)		Kg

Table 7

	Distance and transport modality	unit
a. What is the distance between the drying location and threshing location		meter
b. How did you move the bundles (e.g. walking, by cart, by car)		–

Table 8

	Weight successfully threshed paddy	Unit
Sample 1 (manually harvested)		Kg
Sample 2 (mechanical harvested)		Kg

Appendix C. Instructions to field experts, threshing measurements

General:

- Select 5 farmers from a selected region
- Carry out 3 measurements per farmer
- Use 1 scale for all measurements per farmer, and make sure you calibrate the scale before every measurement
- Use 1 moisture meter for all measurements per farmer, and make sure you calibrate it before every measurement
- Please make pictures of the data collection process when possible

Per farmer:

o 1–2 pictures for harvesting
o 1–2 pictures for drying process
o 1–2 pictures for transport to threshing location
o 1–2 pictures for manual threshing
o 1–2 pictures for mechanical threshing
o 1–2 pictures for any other 'improved' threshing practice

Start

- Visit a farmer and select two plots of 24 m^2 randomly.
  o Preferably the selected plots have the same length and width (e.g. 24 m long/1 m deep, or 12 m long/2 m deep, or 8 m long/3 m deep).
  o Preferably the selected plots are near each other, so that the distance to the threshing place is almost equal for both plots.
- Harvest both plots of 24m^2manually as usual.
  o Make sure both plots are harvested by the same person.
  - Leave both harvested plots in the field to dry as usual.
  o Leave it for 3–4 days, depending on the strength of the sun,
  o At least make sure you dry both harvested plots for the same amount of days.

Step-by-step measurement approach - Rice Olam Nigeria

Threshing

Threshing continuation after 3–4 days.

1. Write down (Table 1):
   a. How many days did you dry the paddy?
   b. On how many days of this drying period a rain shower took place?

 - After drying, move sample 1 to the threshing location.

2. Weigh the total dried plant material + paddy of sample 1 (Table 2).
   o Do the weighing process in several separated bundles that are easy to gather.
   o Place the weighing scale on top of the tarpaulin.
   o Make sure you calibrate the scale before every measurement.
   o When the bundles do not easily fit the weighing scale, please stand on the weighing scale with the bundles of harvested plant + paddy. Take off your own weight from the total weight

3. Write down (Table 3):
   a. What is the distance between the drying place and threshing location?
   b. How did you move the bundles? E.g. walking, by cart, by car

- Start threshing sample 1 manually as usual

4. Weigh the grains that are successfully threshed for sample 1 (Table 4).
   o Make sure you calibrate the scale before every measurement.

5. (When time allows it) Weigh the total plant material for sample 1 (Table 5).
   o Make sure you calibrate the scale before every measurement.

6. (When time allows it) Collect a sample of 5 kg of plant material from sample 1. When not possible, collect a sample of 2.5 kg. Please weigh the exact amount (in kg) (Table 5).
   o Make sure you calibrate the scale before every measurement.

- (When time allows it) Collect the paddy that is still attached to the plant material manually from this smaller sample.

7. (When time allows it) Weigh the paddy that you manually removed from the 5 kg (or 2.5 kg) plant material for sample 1 (Table 5).
   o Make sure you calibrate the scale before every measurement.

- Move sample 2 to the threshing location.

8. Weigh the total dried plant material + paddy of sample 2 (Table 2).
   o Do the weighing process in several separated bundles that are easy to gather.
   o Place the weighing scale on top of the tarpaulin.
   o Make sure you calibrate the scale before every measurement.
   o When the bundles do not easily fit the weighing scale, please stand on the weighing scale with the bundles of harvested plant + paddy. Take off your own weight from the total weight

- Start threshing sample 2 with use of the mechanical thresher.

9. Weigh the grains that are successfully threshed for sample 2 (Table 4).
   o Make sure you calibrate the scale before every measurement.

10. (When time allows it) Weigh the total plant material for sample 2 (Table 5).
    o Make sure you calibrate the scale before every measurement.

11. (When time allows it) Collect a sample of 5 kg of plant material from sample 2. When not possible, collect a sample of 2.5 kg. Please weigh the exact amount (in kg) (Table 5).
    o Make sure you calibrate the scale before every measurement.

- (When time allows it) Collect the paddy that is still attached to the plant material manually from this smaller sample.

12. (When time allows it) Weigh the paddy that you manually removed from the 5 kg (or 2.5 kg) plant material for sample 2) (Table 5).
    o Make sure you calibrate the scale before every measurement.

- Repeat this exercise for this farmer, so in total you should have applied this measurement methodology for threshing 3 times per farmer.

- Repeat this exercise for 5 farmers in total.

If wanted, you can repeat the step-by-step measurement approach for threshing also for other improved threshing practices.

Appendix B. Measurement template, threshing measurements

Table 1

	Drying days and rain showers	unit
c. How many days did you dry the paddy?		days
d. On how many days of this drying period a rain shower took place?		days

Table 2

	Weight total dried sample plant material + paddy	Unit
Sample 1		Kg
Sample 2		Kg

Table 3

	Distance and transport modality	unit
c. What is the distance between the drying location and threshing location		meter
d. How did you move the bundles (e.g. walking, by cart, by car)		–

Table 4

	Weight of successfully threshed paddy	Unit
Sample 1 (manually threshed)		Kg
Sample 2 (mechanized threshed)		Kg

Table 5
(optional)

	Weight plant material and paddy that was manually removed from plant material	Unit
Total plant material Sample 1 (manually threshed)		kg
5 kg (or 2.5 kg) plant material Sample 1 (manually threshed)		kg
Paddy from Sample 1 (manually threshed)		Kg
Total plant material Sample 2 (mechanized threshed)		kg
5 kg (or 2.5 kg) plant material Sample 2 (mechanized threshed)		kg
Paddy from Sample 2 (mechanized threshed)		Kg

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