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Selection of appropriate mechanization to achieve sustainability for smallholder farms: a review

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ABSTRACT

Smallholding farms spread throughout the world, and they consider the cornerstone of agriculture production in Africa and Asia. Smallholder farms produce over 80 % of the food used in most of the developing countries. However, smallholder farmers face many problems, including the lack of appropriate mechanization (AM), labor shortage, increase wages, climate change, and poor access to modern inputs, credit, and markets. The paper focuses on analyzing and proposing the criteria to select and design AM for smallholder farmers through the linkage between farm size, machine scale, and productivity. The machine designers and manufacturers should take some environmental and social implications and machinery support services into consideration to deliver AM to smallholder. The adoption of AM with appropriate planting systems such as CA will ensure sustainability in the production of smallholder farmers. The adherence to these standards with overcoming smallholding challenges will lead to growth and sustainability for smallholder farmers.

1. Introduction

The need to increase productivity, smart management, and sustainability are necessary for smallholder farmers because they are the leading producer of food globally. Almost 500 million smallholding farms around the globe contribute over 80 % of the food used in most of the developing countries (IFAD, 2013). Smallholder farmers dominate the most common farming systems in East and Southeast Asia (ESA) (Rigg et al., 2016) and Sub-Saharan Africa (SSA), where 2/3 of all farms size are less than 2 ha/farm (Altieri, 2009). However, they face some crisis, such as lack of appropriate mechanization (AM), natural resource degradation, climate change, and population growth (Sims and Kienzle, 2017). The world's human population is rising rapidly from 3.7 billion in 1970 to 7.6 billion in 2018 (FAOSTAT, 2019), and in 2050 will reach 9.7 billion (Kassam et al., 2017). Agricultural production in developing countries must rise by 100 % in 2050 to avoid food shortage (FAO, 2014).

The farm power available per area of agricultural land has been stagnating over the past three decades in Southern and Eastern Africa (Baudron et al., 2015). More than 50 % of the lands in Africa is prepared using the hand hoe (FAO and AUC, 2018), while the use of draught animals contribute up to 25 % of farm power in SSA. The blurred vision about the AM for these small farms constitutes a significant limitation for increased land and labor productivity; it impacts the farm operations timeliness and a big source for drudgery. Ploughing with draught animals requires about 60 hours/ha of human labor, while the operation undertaken entirely by hand requires 500 hours/ha (Sims and Kienzle, 2006). In most African countries, smallholder farmers have

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increasingly used land, water, fertilizer, and chemical nutrients to raise farming productivity while ignoring farm power. AM is necessary (Diao et al., 2012) due to labor shortages, increasing of wages (Sims and Kienzle, 2006), and the decline of draught animals, which is affected by diseases, recurring droughts (Mrema et al., 2008), and feed shortages (Tegebu et al., 2012).

The large-scale mechanization promotion in SSA in the 1950s raised concerns between small farmers because of labor displacement and small farms consolidation. Thus, the term "appropriate mechanization" appeared in the 1970s (Mrema et al., 2008). But the developed small machines during that period failed in the market (Holtkamp, 1990). There is an urgent need to establish standards and foundations for defining AM, considering the proper agricultural systems and linking the various product components. AM means user-friendly machinery tailored to smallholder farms, suitable to local agronomic conditions, and limited resource endowments (Mottaleb et al., 2016; Van Loon et al., 2018). Also, Economically feasible, environmentally sensitive, and socially acceptable lead to sustainable agricultural mechanization (SAM) (Sims and Kienzle, 2016). Furthermore, AM should improve productivity, enhances market access, and contributes to mitigating climate-related hazards. AM argues that machines should adapt to farm size and not the opposite (Baudron et al., 2019).

The highest productivity comes from AM use with other components of the farming system and the sequencing of their introduction (Mrema and Odigboh, 1993). The paper aims to analyze and propose the criteria for selection of AM for smallholder farms through the linkage between farm-scale, machine size, farming system, and productivity to help in delivering SAM technologies to smallholding farm families. This paper discusses the challenges which face smallholder farmers and how to reach the market. It opens the way to more researches to design AM, which has acceptable and adoption from smallholder farmers.

2. The criteria for appropriate smallholder farms mechanization

Supporting evidence exists to illustrate the link between farm power and farm productivity (Baudron et al., 2012), where increasing agricultural output usually requires additional farm power (Clarke Lawrence and Bishop, 2002). The most common challenges to deliver AM to smallholder is the mismatch between machines scale, economies, and farm size. Smallholding farms consist of separate and dispersed fields. Thus, they are poorly suited for more massive machinery (Harman, 2016; Krupnik et al., 2013; Wolfenson, 2013). So, Agricultural machinery designers must take some considerations when manufacturing AM for smallholding farms, as shown in Table 1 to achieve the adoption and sustainability for these machines.

Table 1
Some considerations for smallholding AM.

Environmental implications	• Soil degradation: 22 % of productive land is affected by some form of degradation in Africa (Jones et al., 2013). • The emissions of GHG: Agriculture activities account for 20–22 % of global CO_2 equivalent GHG emissions (FAO, 2017).
Designing and developing (Faleye et al., 2012)	• Machines should be compact, light, low powered, and multi-purpose. • Locally-available materials for manufacturing. • Safety and comfort. • Manufacturing mini-power tillers (PT), small farm tractor, and equipment. • Using energy-efficient machines by harnessing renewable sources of energy.
Social implications	• Total labor requirements, tasks division between household members, and impact on the quality of life (Bishop, 1997). • Economic conditions in which farm households (Sims and Kienzle, 2006).
Machinery support services	• The ability to current infrastructure to accommodate the new technologies, access to technical information, spare parts, training, and advisory services (Bishop, 1997).

3. Three models for mechanization

According to some Asian countries' experiences in which smallholders dominate, three models in India, China, and Bangladesh (Baudron et al., 2015) could deliver AM for smallholding farmers in Africa and Asia (Diao et al., 2012).

3.1. The Indian model has high public support from the government for the purchase machines and four-wheel tractors (4WTs) (Hazell, 2009; Singh, 2006). This level of available support is currently unlikely to occur in most of ESA and SSA due to fiscal limitations. This model support medium and large scale farmers and leaving many of the smallholder farmers without access to AM (Biggs et al., 2011).

3.2. The Chinese model based on the migration of specialized equipment and thus requires a high-quality rural road network and large agro-ecological areas with rainfall gradients, which is absent in many ESA countries (Dixon et al., 2001) and some SSA countries.

3.3. Bangladesh's agriculture relies on small machines such as two-wheel tractors (2WTs). Almost 80 % of the cropland in Bangladesh are prepared mechanically (Kulkarni, 2009), and one in thirty farmers owns one of the 2WTs (Justice & Biggs, 2013). That means every 2WTs owner considers a service provider, and most of the 2WTs users can access AM by hiring service providers. This Bangladeshi model appears acceptable as even the most impoverished farmers have access to 2WTs without support from a formal financial institution, due to 2WTs cheaper than animal traction using or 4WTs (Roy and Singh, 2008). Also, the multiple purposes for 2WTs, such as post-harvest operations, water pumping, and transport, leads to high annual rates of earnings for 2WTs owner (Biggs et al., 2011; Diao et al., 2012).

4. Farming systems and conservation agriculture (CA)

Farming systems describe the pattern of agricultural enterprises and their interactions with including all factors on-farm family livelihoods, social, and environmental factors (Dixon et al., 2001). The select appropriate farming system is necessary to select AM for smallholder farms. The farming system should provide enhancing soil organic matter, minimizing mechanical soil cultivation, water management, and the use of drought-resistant crop varieties (Sims and Kienzle, 2017) to achieve sustainable crop production (Gibbon, 2011).

Traditional agriculture and CA are the essential farming systems that spread in smallholder farms. Conventional tillage is one of the most energy-consuming in agriculture operations where switching from moldboard ploughing to direct seeding reduces the total annual fuel consumption from 92 to 42 L/ha. The emissions of GHG represent 35.3, 7.9, and 5.8 kg CE/ha for traditional till, minimum-till, and no-till method, respectively (Lal, 2004). On another side, CA offers provision energy, limiting soil erosion, saves labor, reducing fertilizer, make the crop more resistant to drought, and reduced the total cost production (Sims and Kienzle, 2006). CA is a complementary set of three general principles: minimal soil disturbance, mulching, and crop rotation (Kassam et al., 2009; Mkomwa et al., 2017). Reducing tillage operations reduce production costs where the saving in operations time/ha is almost 40 % with conservation agriculture, as shown in Table 2 (Sims and Kienzle, 2006). Based on the previous evidence, we can choose the CA farming system for smallholder farms.

Table 2
The time required for CA and conventional tillage operations.

Operation	Conservation agriculture (hours/ha)	Conventional tillage (hours/ha)
Knife roller	0.89	-
Direct seeding	0.76	-
Spraying	1.2	0.6
Harvest	0.93	0.93
Ploughing/disking	-	1.37
Leveling	-	1.38
Conventional planting	-	0.89
Earthing up	-	1
Total	3.78	6.17

5. Mechanization of CA

Mechanization of farming systems includes all types of implements and devices for applying power on the farm, such as tractors, ploughing, harrows, seeder, planters, cultivators, harvesters, and haying machines (Aduayi and Ekong, 1981). Mechanization of CA maintains soil capacity of production (Chivenge et al., 2007), and direct seeding minimizes the energy needed by about half compared to conventional ploughing (Lal, 2004). These advantages of CA stimulate smallholders to adopt CA mechanization (Sims and Kienzle, 2017).

5.1. The tractors

The tractor is the primary mover for all the implements, the most used, the most prone to wear, and the most costly item of all farm machinery (Ellis and Wainwright, 1994). So, Smallholders are unable economically to own 4WTs (Sims and Kienzle, 2006). In Africa, the mechanization tends to rely on 4WTs with a range of 38 to 68 kW (Cabral, 2016). But recent development initiatives and researches are taking place in Africa to the potential of using 2WTs for agricultural mechanization in areas dominated by small fields (Baudron et al., 2015; Kahan et al., 2018). The 2WTs (Fig. 1) and other small engines can satisfy the power needs of small farms (Biggs et al., 2011). The 2WTs are probably more attractive for smallholder farms and service providers (Baudron et al., 2015) due to the lower capital needed for purchase, operation, and maintenance of 2WTs more than 4WTs (Diao et al., 2012). In small fields, 2WTs have higher efficiency more than 4WTs due to the 4WTs spend more than 50 % of their time lifting the implement, turning, and positioning for the next run. The 2WTs is lighter in weight than a 4WTs and so exerts less ground pressure and results in less soil compaction (Holtkamp, 1990; Singh, 2006).

Fig. 1. Chinese Two Wheel Tractor.

Fig. 2. Power tiller for rice farms.

Although Japanese and Korean 2WTs have high quality compared to Chinese 2WTs, their cost is more than double. So, the 2WTs in the Bangladesh market is dominated mainly by Chinese 2WTs (Biggs et al., 2011) due to 2WTs are cheap and 'good enough'. The experience in Nigeria proved the appropriateness of power tiller (PT) using (Fig. 2) in increasing small farms' productivity (Fashola et al., 2004). The PT is one of the 2WTs types with a simple two-stroke engine, 13-horse power hand-driven, equally a multi-functional and multi-purpose, and affordable (Faleye et al., 2012). The previous factors illustrate the spread and profitability of 2WTs in Bangladesh and elsewhere in South and Southeast Asia. Substituting 2WTs for oxen would save several tons of biomass, which is consumed by draught animals every year in many areas of Southern and Eastern Africa where animals traction is essential and also involving the private sector through business model development (Baudron et al., 2015).

5.2. Seeders and planters

African smallholders face a lack of appropriate implements to seed at the correct depth through the soil cover and with minimum disturbance of soil, which constraint was adopting CA (Giller et al., 2009; Hobbs et al., 2008; Johansen et al., 2012). Several mechanization options appear for direct seeding (Johansen et al., 2012) from countries such as China, India, and Brazil and can be used to seed most large and small grain crops (Sims et al., 2017).

Based on seed placement technologies used, two wide categories of CA seeders can be considered rotary strip-tillage seeders (Fig. 3) and tow-behind or toolbar-based seeders (Fig. 4). They have low draught requirements; therefore, they can be used up to six openers without the need for additional weight to penetrate the ground (Ritchie et al., 2007; Justice et al., 2004). But they tend to disturb large volumes of soil, incorporate crop residues high percentage, and cannot be used in rocky soils (Ritchie et al., 2007). There are seeders for one row, and more depend on human pushing (Fig. 5). Jab planter is another type for hand seeder which can deliver seed and fertilizer through different sharp beaks that are closed on entering the soil and opened at planting depth (Fig. 6). It can plant very effectively into mulch-covered ground, but the tips clog if the mud is too sticky (Corsi and Muminjanov, 2019).

Taken by: Israil Hossain

Fig. 3. Two-wheel tractor zero-till drill.

FAO/J.Kienzle

Fig. 4. Animal-drawn seeder.

Johnny' s selected seeds Company

Fig. 5. Seeders equipment with one row and more.

FAO/TECA

Fig. 6. Jab planter.

5.3. Cover crop and weed control management

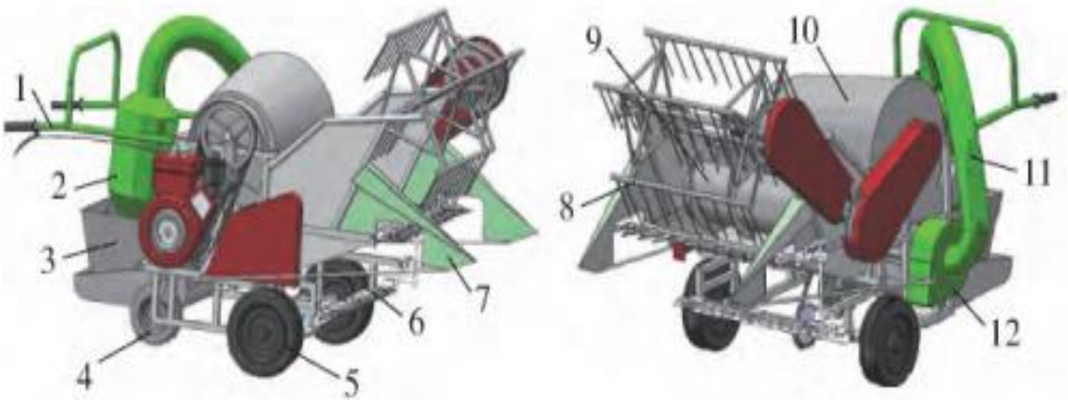
CA aims to reduce the use of herbicides, where Keeping the soil covered with plants will inhibit weeds and cover crops that contain a broad mixture of species that may be the best option. But in the case of herbicides spraying, A 20-liter backpack Sprayer with a single-nozzle is the best suited for small farms, and choosing the right nozzle is very important, as it can save money and time (Corsi and Muminjanov, 2019). Mechanically, covered crops, residues, and weeds can be managed with knife rollers before direct drilling - knife rollers are cylinders with blades that wrinkle plants without cutting them. In many cases, this is enough to kill weeds (Sims and Kienzle, 2017).

5.4. Harvesting machines

The harvesting machinery must not only ensure reliability, performance, and production efficiency but also consider adaptability and economical. The machine must meet the roads and transfers in the hilly and mountainous areas, and it can complete the operation of small fields, corner turns, and field harvesting with a certain depth. Economically, the first is to consider the purchasing power of farmers in the hilly and small areas, so the operating parts are simplified during design, and the production cost is reduced; the second is to improve the smoothness of operations and ensure production efficiency (Fig. 7) (Dai et al., 2016).

The harvesting in smallholder farms should be with an appropriate harvester to get high efficiency. For example, a small harvester with feed quantity 0.52 kg/s, impurity rate was 0.64 %, seed broken rate was 0.13 %, the total loss rate was 1.18%, the seed remains rate was 0.02 %, and productivity could reach 0.18 ha/h was in smooth operation (Table 3) (Fei et al., 2016).

In Okinawa, the small harvester for a green cane showed higher performance, such as work capacity and productivity more than the medium harvester. So, farmers should replace the large and medium harvester with the small harvester (Shinzato et al., 2015).



1. Operating the armrest, 2. Cyclone separator, 3. Grain bin, 4. Tailwheel, 5. Walking wheel. 6. Double-layer harvest header, 7. Grain divider, 8. Reel, 9. Conveyor, 10. Retractable finger type cone threshing device, 11. Suction pipe, 12. Suction fan.

Fig. 7. Small harvester components for hilly and smallholder farms.

Table 3.
The specifications of the small harvester.

Parameters	Design value
Dimensions (length × width × height) mm^3	1980 × 1060 × 1120
Cutting width / mm	1000
Supporting power / kW	5
Feeding method	Half feed
Feeding amount / (kg/s)	0. 40 ～ 0. 60
Total loss rate / %	≤1. 26
Seed breakage rate / %	≤0. 16
Miscibility / %	≤1. 8
Delayed rate / %	0
Productivity / (ha/h)	0. 16 ～ 0. 20

6. Smallholder farmers challenges

The smart management based on three themes, productivity-increasing through AM, reduced GHG emissions through carbon sequestration and reduced fuel consumption, and adaptation with climate change manifestations (Campbell and Dinesh, 2017). Overall, climate and soil resources play a significant role in the small farmer's ability to seize opportunities in their quest to achieve particular livelihood objectives (Snapp, 2017). Several countries in Africa, like Ethiopia, South Sudan, Uganda, and Kenya, have experienced rise trends in annual mean temperatures over the past years (Funk et al., 2012). The crop yield may fall in Africa by 10–20% in 2050 or even up to 50% associated with the impacts of climate change (Thornton et al., 2006). However, smallholder farmers have weak knowledge around climate change impacts on water, agriculture, energy, etc. (Hundera et al., 2019). Smallholder farmers always depend on mild weather to reach food-secure, but with climate change effects, smallholder production systems are in danger, and they need to smart management for climate agriculture (Sims and Kienzle, 2017).

Another challenge is a mismatch between the scale of machines, farm size, and economies. Smallholder farmers cannot purchase equipment due to high machines cost in many Asian and African countries. The financial support through subsidies or financing schemes is limited, and the financial-service sector avoids providing credit to smallholders due to lack of perception of the high risk and eligible collateral involved with agriculture (Clarke L.J., 2000; Holtkamp, 1990; Mottaleb et al., 2016; Mrema et al., 2008). The introduction of AM needs addressing farmer's education and capacity, which produces skilled people able to use, repair, and maintain equipment (Diao et al., 2018). The service introducers often fail to increase AM access for smallholders due to insufficient support of other complementary actors involved with supply, sales, distribution, manufacturing, and after-sales services (Clarke L.J., 2000; FAO and UNIDO, 2008; Pingali et al., 1987).

7. The reach to market and the policymaker

The delivery of AM and reach to market by smallholders should be taking some considerations. The facilitating emergence of private rural service providers, taking into consideration the need for a broker. Linking AM and other input business models with output business models. Expand the range of services offered, bundling hiring services, and providing direct subsidies for private sector investment in AM service supplying. The previous experiences in market development, proving that the reach to market and promotion to AM for smallholding can be applied without farms consolidation, as we see in the Bangladesh case (Biggs et al., 2011). Farm scale, local wage values, youth migration, access to credit services, and agricultural cooperatives activities with farmers positively influence smallholder farmers' readiness to pay for buying of AM. Simultaneously, the number of draught animals owned for smallholders has negatively impacted (Paudel et al., 2019).

About 83% of PT owners in Bangladesh use their PT to cultivate other farms far from their locality, besides cultivating the land in their locality. The average distance of places where an individual PT moved to cultivate land varied from 5 to 40 km. Thus, it is important to recognize that small farmers got increased access to PT ownership through purchase and that they also benefited from PT service market (Alam et al., 2004). Again, smallholder access to tractor power can come from national government tractor hire schemes, local government small-scale hire schemes, groups are working at the grassroots level and providing service from donated funds, and private sector entrepreneurs. The best option of AM, whether powered by engines, animals, or humans, will depend on labor costs, credit availability and interest rates, market for increased crop production, availability of machines, rates of use of machines, farm size, the availability of spare parts, fuel, and repair services of engine powered mechanization (Sims and Kienzle, 2006).

The adoption and utilization of AM from smallholder farmers depend on information spreading activities through multimedia, fairs, and exhibitions, and similar style have to be actively pursued in strategical locations where AM are actually needed, Training the local craftsmen in manufacturing technology, repair, operation, and maintenance to promote local manufacturing of agricultural machinery. Farmers' cooperatives can also be tapped, particularly in build-up mutual use of various modern farm facilities and machinery. Government-private sector complementation is essential in promoting AM. The policymakers could establish service centers in rural and remote areas; and assist smallholders through continuing financial assistance, loans, and subsidies to provide machinery owners and users of continued farm production operations (Faleye et al., 2012).

8. Conclusion

The smallholding farms consider a big problem when it comes to mechanization due to it is opposite the "economies of scale". Not only AM increases smallholder farms productivity but also how to use this mechanization with other components of the farming system as CA to get the highest productivity. The barriers which impede the sustainability and growth of AM industry and programs class into technological, sociocultural, behavioral, financial, economic, and environmental issues.

To select AM for smallholding farms should identifying tasks to be mechanized (low labor productivity, high labor drudgery, willingness to hire services to perform these tasks), identifying and manufacturing suitable machines and adapting them if necessary, Creating demand (incentives for commercial actors) through aggressive demonstration, Supporting the multiple markets around the small engines and 2WTs-based mechanization through market linkages, promotion, capacity-building, and access to finance. Access to AM by smallholder farmers is an urgent necessity to allow increases in their labor and farm productivity. All of these will require clear guidance from the public sector to provide a climate conducive to enthusiastic and profitable private sector participation. The policymakers should encourage and facilitate the local manufacture of AM inputs. Also, to increase the mechanization services, demand should create and nurture public interest farmer groups (such as CA clubs) and provide credit and financial incentives.

This paper opens the way to design AM for smallholding farms through some criteria and illustrated the challenges which face the smallholder farmers through connect between farm size, machine size, and productivity.

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اختيار الميكنة المناسبة لتحقيق الاستدامة لأصحاب الحيازات الصغيرة: بحث مرجعي

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الملخص العربي

تنتشر المزارع الصغيرة في جميع أنحاء العالم، وتعتبر حجر الزاوية في الإنتاج الزراعي في إفريقيا وآسيا. تنتج مزارع أصحاب الحيازات الصغيرة أكثر من ٨٠٪ من الأغذية المستخدمة في معظم البلدان النامية. ومع ذلك، يواجه المزارعون أصحاب الحيازات الصغيرة العديد من المشكلات، بما في ذلك الافتقار إلى الميكنة المناسبة (AM)، ونقص العمالة، وزيادة الأجور، وتغير المناخ، وضعف الوصول إلى المدخلات الحديثة والتمويل والأسواق. يركز هذا البحث المرجعي على تحليل واقتراح المعايير لاختيار وتصميم الآلات الزراعية للمزارعين أصحاب الحيازات الصغيرة من خلال الربط بين حجم المزرعة وحجم الماكينة والإنتاجية. يجب أن يأخذ مصممو الآلات والمصنعون بعض الآثار البيئية والاجتماعية وخدمات دعم الآلات في الاعتبار لتقديم الميكنة الزراعية إلى أصحاب الحيازات الصغيرة. كل ما سبق بالإضافة إلى أنظمة الزراعة المناسبة مثل الزراعة المحافظة يؤدى إلى الاستدامة في إنتاج أصحاب الحيازات الصغيرة. سيؤدي الالتزام بهذه المعايير مع التغلب على تحديات الحيازات الصغيرة إلى النمو والاستدامة لأصحاب الحيازات الصغيرة.