Heliyon 10 (2024) e36695

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

A review of appropriate mechanisation systems for sustainable traditional grain production by smallholder farmers in sub-Saharan Africa with particular reference to Zimbabwe

Tinashe Madzivanzira [a], Brighton M. Mvumi [a,*], Raymond M. Nazare [a,b], Elijah Nyakudya [c], Florence Mtambanengwe [c], Paul Mapfumo [c]

[a] *Department of Agricultural and Biosystems Engineering, University of Zimbabwe, Zimbabwe*
[b] *Currently Independent Agricultural Engineering Consultant, Zimbabwe*
[c] *Faculty of Agriculture, Environment and Food Systems, University of Zimbabwe, Zimbabwe*

ARTICLE INFO

Keywords:
Conservation agriculture
Climate change
Farm power
Mechanisation technologies
Mechanised crop establishment

ABSTRACT

Climate change and variability is affecting the production of maize, a staple food in Zimbabwe, leading to the advocacy for production of traditional grains (sorghum, pearl millet and finger millet) as complementary crops for food and nutrition security; mainly because of their drought tolerance. Adoption of traditional grains as a climate change adaptation strategy is, however, limited by lack of appropriate field mechanisation technologies, *inter alia*. The specific objective of this review was to examine the field mechanisation technologies being used in different farming systems across the globe for their appropriateness in smallholder traditional grain production systems in developing countries, using Zimbabwe as an example, and focusing on the prevailing technical, socio-economic and environmental factors which influence sustainable adoption. The review was conducted by searching ScienceDirect, Researchgate, JSTOR, Springer, AGORA and Google Scholar databases for mechanisation strategies, policies, machinery and equipment used in cereal production systems across the globe. The review revealed that the mechanisation of traditional grain production operations is lagging behind that of other cereals and that there is need to work on developing appropriate mechanisation systems for smallholder farmers in developing countries. Various farm power options were analysed and the use of two-wheel tractors under service-provision was identified as the most suitable option. Conservation agriculture-based direct seeders and use of mowers or bio-pesticides are the best-suited technologies for crop establishment and weed control, respectively. In terms of harvesting, no available equipment can be recommended for smallholder use as yet. Further research is required to optimize the practical application of mowers and bio-pesticides as well as develop scale-based direct seeders and harvesting equipment. Policy issues were identified and recommendations for improvement made. The findings of the current study can be adapted by other sub-Sahara Africa countries where farming systems, priorities and challenges are similar to that of Zimbabwe.

* Corresponding author.
E-mail addresses: mvumibm@agric.uz.ac.zw, mvumibm@hotmail.com (B.M. Mvumi).

https://doi.org/10.1016/j.heliyon.2024.e36695
Received 21 February 2024; Received in revised form 17 August 2024; Accepted 20 August 2024
Available online 22 August 2024

1. Introduction

Agriculture is a critical sector of the Zimbabwean economy, contributing about 60 % of inputs into manufacturing, 40 % of export earnings and consuming much of the outputs from industry [1]. About 33 % of Zimbabwe's formal labour is found in agriculture and at least 70 % of the population derive their livelihood from this sector [2]. The social, economic and political lives of most Zimbabweans relies on agriculture [3]. Maize (*Zea mays* L.) is the staple food in Zimbabwe and most sub-Sahara African countries, and is the most cultivated field crop in terms of area under production. About 80 % of the population of Zimbabwe cultivates maize either for domestic consumption or for sale of the surplus [3].

Maize productivity in Zimbabwe is low with a national 20-year average yield of 0.75 t/ha (Fig. 1) [4] against a yield potential of at least 10 t/ha for most varieties suitable for production by smallholder farmers [5,6]. This can be attributed to the socio-economic challenges being faced by the nation [3], which cause insufficient input supply. Continuous use of retained maize seed which is characterised by low yield potential, by the majority of smallholder farmers due to unaffordable hybrid seed prices, high fertiliser requirements for hybrid seed as well as resistance to shift to new technologies is contributing to the low maize yields being realised [5]. It costs about USD 1140 to produce 1 ha of a maize crop [7]. However, smallholder maize farmers in Zimbabwe are resource-poor and cannot afford the highly priced hybrid seed [8], as well as the large quantities of fertiliser in excess of 400 kg/ha basal and 450 kg/ha top-dressing required [7]. On one hand, these smallholder farmers are resource-poor, with no stable income. On the other hand, the farmers lack access to agricultural credit facilities as they cannot meet the collateral conditions while at the same time they cannot raise enough finance required to purchase the inputs [9]. Consequently, smallholder farmers end-up using retained seed that has low yield potential while also applying insufficient inorganic fertiliser to the crop, leading to poor crop yield. Other factors contributing to low crop yields are: poor soil conservation management, poor water management, poor soil nutrition management and poor pests and diseases management. Although the afore-mentioned factors contribute to the low maize yields obtained in Zimbabwe, the largest contributor is actually climate change and variability [10,11]. Smallholder farmers practising rain-fed agriculture are exposed to risks such as erratic rainfall and prolonged dry spells, which is affecting crop productivity [12].

There is consensus among experts in different fields of study that climate change is a reality [13] and is negatively affecting crop productivity, especially maize [14]. There is, therefore, need to develop adaptation strategies to the changing climate and reduce its effects on agriculture. Specifically, there is need to reduce dependence on maize and increase use of traditional grains which are more climate-resilient crops [15]. These traditional grains are: sorghum, *Sorghum bicolor* (L.) Moench; pearl millet, *Pennisetum glaucum* (L.) R. Brown; and finger millet, *Eleucine coracana* (L.) Gaertn. Sorghum is laborious in terms of production and processing and requires attention as compared to maize [16]. Lack of knowledge, resources and markets; and inadequate availability of certified seeds to smallholder farmers also contribute to low levels of production [16]. High labour demand is also a major constraint to sorghum production since many people in rural areas are of old age [16] as the young and virile have migrated to urban areas in search of better paying jobs. Mechanisation can be a strategy to address labour challenges and to enhance the precise utilisation of the scarce inputs such as fertiliser and seed. Mechanisation can also help attract the young and virile people back into agriculture because of the reduced drudgery and the increased productivity.

As there is a strong justification in favour of shifting towards traditional grain production, the current paper critically reviews the different mechanisation technologies used in the production phase of these grains and identifies those that are appropriate for uptake

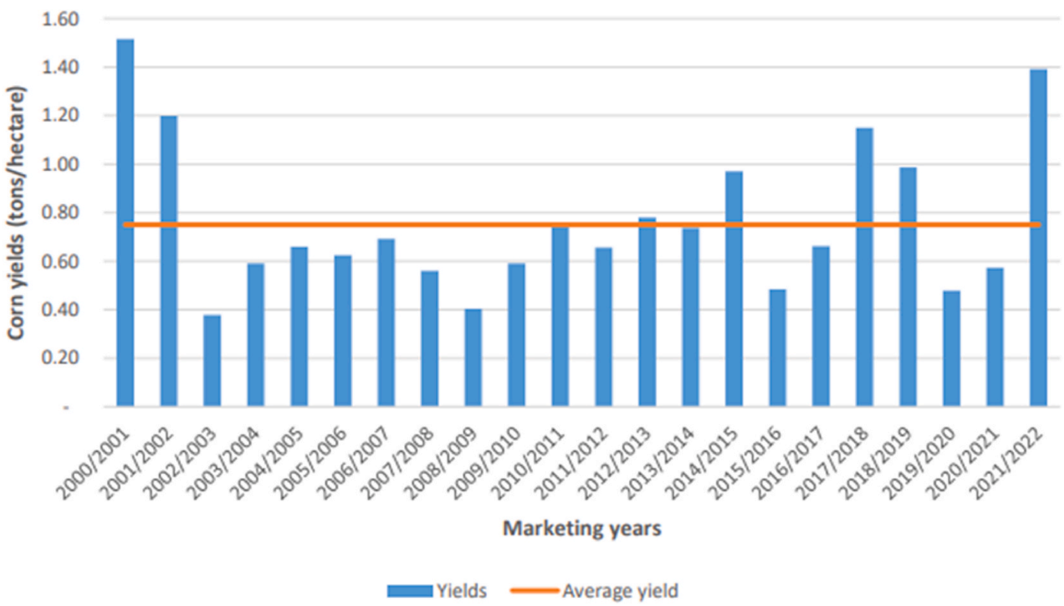

Fig. 1. Zimbabwe 22-year average national maize yield *Source* [4].

by small-scale producers in developing countries such as Zimbabwe. The technologies were analysed, taking into consideration the technical, social, economic and environmental factors prevailing in Zimbabwe. The paper starts by analyzing the different power sources available for adoption by Zimbabwean smallholder farmers in traditional grain production operations. Next is an analysis of the different equipment and implements that can be adopted for traditional grain production. In conclusion, the paper summarises the key findings of the review and proposes a policy framework and research and development agenda based on the findings.

2. Methods

During the reviewing process, various scholarly databases and search engines were used to access the relevant information. These included AGORA, ScienceDirect, Web of Science, Google Scholar, and JOSTR for accessing of credible and reliable information. Grey literature sources, for example, published conference proceedings and reports prepared by organisations involved in agricultural research and development were reviewed. These included but not limited to publications by the Consultative Group for International Agricultural Research (CGIAR), and United Nations (UN) agencies. Scientific articles from both the developing and the developed countries were used. Information about: (i) the challenges in sorghum, pearl millet and finger millet production, (ii) the characteristics, advantages and limitations of manual power, draught animal power (DAP) and motorised power as power options in smallholder farmer production systems, and (iii) the different strategies for mechanising the production operations from planting to harvesting of sorghum, millets and related crops such as rice and wheat; was used. Terms searched for included, but not limited to, combinations of the following: "traditional grains", "small grains", "sorghum", "pearl millet", "finger millet", "millets", "climate change", "mechanisation", "conservation agriculture", "direct seeding", "transplanting", "plant population", "production", "weed control", "harvesting", "labour", "machinery", "equipment", "draught animal power", "tractor power", "2-wheel tractor"; *inter alia*. Various combinations of search terms were used including: "climate change + maize + small grains + Zimbabwe", "small grains + harvesting + machinery" and "Farm power + smallholder farmers +2 wheel tractor +4 wheel tractor + animal power". The review covered papers published in English from 2000 to 2024. Publications emanating from the sub-Saharan Africa as the focus area as well as publications produced from regions with vast traditional grain production such as Asia and America were used. Articles on primary and secondary processing were excluded since the review's focus was on the mechanisation of the field operations during traditional grain production. The thematic analysis approach was used to categorise and synthesise the gathered information. The themes were developed around; the history, status quo and future prospects of traditional grains as a climate change adaptation strategy, mechanisation of traditional grain production operations with focus on power and equipment options used in specific operations as well as the policy considerations for successful mechanisation of traditional grain production operations.

3. Importance of traditional grains

3.1. Climate resilience

Researchers have reported that traditional grains, are better performers under the adverse conditions of climate change compared to other grain crops for example maize [17–19]. Sorghum and millets are adaptive to regions with erratic rainfall and poor soils and have lower risk of failure compared to other cereal crops [20]. Adoption of traditional grains is a reliable adaptation strategy to climate change as they provide relief through improved food availability and accessibility in affected areas of Zimbabwe [15]. Research conducted in Binga, Gutu and Mangwe districts in Zimbabwe showed that traditional grains are adaptable to conditions of high temperatures, low rainfall and soils of poor fertility [15,17,21] and are a source of relief food in cases of drought when maize production fails [18,22].

3.2. Food and nutrition security

Traditional grains can contribute towards the provision of food and nutrition security to the Zimbabwean population. The resilience of traditional grains to harsh conditions of low moisture and high temperatures [17], means that they can survive the envisaged drought conditions to produce substantial grain for farmers to harvest where maize cannot perform. During drought periods, traditional grains can reduce food shortages and enhance food accessibility [17].

Traditional grains are also nutritionally rich, for example, sorghum is gluten-free and contains almost all classes of phenolic compounds [23]. Phenolic compounds possess a wide range of biological activities such as antioxidant, anti-inflammatory, and antimicrobial properties [24]. Long-term consumption of diets containing phenolic compounds protects against cancer, cardiovascular disease, diabetes, osteoporosis, and neurological diseases [24,25]. Finger millet grain is rich in fibre, iron and calcium. It contains 10 times higher calcium content than that found in its biggest counterpart maize and three times higher than that of milk [26]. Only 100 g of finger millet grain is sufficient to provide for daily calcium requirement for humans [27]. Because of its nutrition, finger millet is suitable for use in baby weaning foods, food for lactating mothers and food for people with underlying health problems and those suffering from malnutrition. Besides being gluten-free, pearl millet grain contains essential micronutrients such as zinc and iron [28]. Pearl millet contains at-least 4 mg/100g and 3 mg/100g of iron and zinc respectively whilst maize contain at-least 1.22 mg/100g and 1.75 mg/100g of iron and zinc respectively [29,30]. At-least twice the quantity of maize is required to provide as much iron and zinc as provided by pearl millet. Given the high concentration of essential micronutrients and other health-enhancing properties within the grains, consumption of traditional grain-based foods can enhance the health of the consumers. Porridge from traditional grains is often recommended to sick people in most rural areas, whereby traditional medicine can also be added especially as powders (Personal observation).

The production of traditional grains also have some economic benefits such as generation of income and employment creation through selling of grain and involvement in grain processing and marketing activities, respectively. Traditional grain farmers sell their produce to the Grain Marketing Board of Zimbabwe, contractors or some informal markets. However, in most cases, the selling price is low and does not justify traditional grain production as an income-generating activity; hence most smallholder traditional grain production is done for subsistence [31]. Several processing players including millers, beer brewing companies and stock feed manufacturing companies who also happen to be the traditional grain contractors, exist in Zimbabwe [31]. These enterprises create employment for the Zimbabwean population. Traditional grains also have some socio-cultural significance. These include: use in brewing beer for the rain-making ceremonies, the production of local beverages served during important events such as weddings and memorial services, and use in ancient times for payment of bride price [21]. However, the quantities required for these socio-cultural purposes tend to be small at any given event.

4. Factors limiting adoption of traditional grains

Despite the advantages of traditional grain production in the face of climate change, and food and nutrition insecurity, it is evident that their adoption for production and consumption in Zimbabwe is limited [19]. This is because traditional grain production is associated with poor yields, high labour demands, high production costs and little or no profits [17,19]. Low yields in traditional grain production can be attributed to the negative effects of pests, diseases and poor inputs [18,32]. The common pests that are detrimental to traditional grains include quelea birds, shoot fly and armoured crickets [16]. The average yield levels for traditional grains in Zimbabwe are: sorghum *(0.32 t/ha)*, pearl millet *(0.3 t/ha)*, finger millet *(0.24 t/ha)*, against the expected yield levels of 2–4 t/ha [19]. Even-though traditional grains are said to be better performers than maize, their yield levels are still way below that of maize which is on average *0.75 t/ha* (Fig. 1). It is for this reason that farmers still opt for maize production over traditional grains [16,19]. Improving the yield levels of traditional grains through improved genotypes, nutrition, farming systems and crop management strategies is a must if widespread production of traditional grains is to happen.

The high labour demands involved in traditional grain production [18]. Traditional grains require more labour to produce than maize [19]. Establishing 1 ha of sorghum requires about 220 man-hours (Table 1) compared to about 76 man-hours for maize [33], with the thinning operation in sorghum production requiring the most labour. The excessive labour requirement in sorghum is a deterrent factor to the younger generation and the elderly; a situation exacerbated by rural-urban migration of the youths.

Lack of formal markets that offer competitive and viable producer prices, inadequate government support as well as consumer preferences that favour maize and its products are additional factors that are contributing to non-adoption of traditional grains by Zimbabwean farmers [19]. Delta Corporation Limited and the Grain Marketing Board of Zimbabwe are the two forms of formal markets for traditional grains in Zimbabwe, offering a producer price of about USD 250 per MT of grain, with Delta Corporation targeting mainly red sorghum [35]. Given the low yield levels and the current producer price, the total income per ha is, therefore, unable to meet the break-even cost per ha of about USD 1000; hence farmers are operating at a loss. Lack of diverse and more-friendly processing technologies for the value addition of traditional grains is also hindering widespread adoption of traditional grains [19].

Adoption of traditional grains for production by farmers will only be successful if the production systems are profitable and if enough grain is produced to ensure food security and for marketing. Crop yields, production costs and grain quality issues need to be addressed for effective traditional grains adoption to occur. One strategy to boost economic production of traditional grains is the use of mechanisation.

5. The role of mechanisation in traditional grain production

Mechanising the field crop production operations is an important tool in improving crop yields, reducing production costs and

Table 1
Comparison of labour and labour cost requirements to establish 1 ha of sorghum (assuming a 3-men team for DAP + manual power option and 1-man + 2-row conservation agriculture-based planter for the 2-wheel-tractor option) Source: [34].

Field operation	Labour requirement per operation (man-hours) according to power-source	
	DAP + manual	2WT + CA planter
Ploughing	49	0
Harrowing	8	0
Row marking	13	0
Planting/drilling	15	7
Basal application	15	0
Covering	8	0
Thinning	112	0
Spraying herbicide (pre-emergence)	0	1
Total (man-hours)	**220**	**8**
Man-days	**27.5**	**1**
Labour cost/Ha (at 3 USD/day)	**82.5**	**3**

DAP = Draught Animal Power; 2WT = 2-Wheel Tractor; CA = Conservation Agriculture improving grain quality and can transform the current state of traditional grains production in Zimbabwe. Agricultural mechanisation is the scientific and systematic provision and use of tools, equipment and machinery in undertaking agricultural operations [36]. It is also a process whereby labour along the entire agricultural value chain is replaced by other sources of energy such as animal power, fossil energy or renewable energy [37].

The production of traditional grains under CA includes operations like seeding when the seed is planted, pest control to control weeds, pests and diseases and harvesting. During the seeding operation, direct seeders with capacity to effectively plant the small-sized seed at the correct depth, inter-row spacing and in-row spacing are required. These seeders must also have capacity to handle surface mulch and unploughed land. In terms of pest control, equipment that effectively control the pests without disturbing the soil are required. Harvesting equipment with ability to handle the produce without excessive grain damage as well as minimised contamination with extraneous material for example soil is a requirement.

Improved timeliness of operations, precision in seed and fertiliser placement, efficient application of pesticides and reduction in losses at different production stages are all yield-enhancing factors of mechanisation [38]. Studies have shown that agricultural mechanisation reduces labour requirements, reduces production cost and increases farmers' income [38]. It also reduces the time spent on traditional grain production as well as making it more efficient [39]. The ultimate goal of mechanisation is to optimize production and productivity at the least possible cost [40]. A study in Mali showed that mechanising sorghum production operations reduced labour requirements by 74 % [41], whilst Nourou et al. [42] reported a 71 % reduction in the time required to complete sowing and weeding in pearl millet production systems in Niger. Nourou et al. [42] also reported that the gross margin in mechanised pearl millet production systems was 80.2 % higher than that of manual production systems.

Previous efforts to promote agricultural mechanisation in Africa have, however, failed due to use of wrong implementation strategies and delivery of inappropriate technologies [36]. For example, the government-led mechanisation programmes that focused on tractor-hire schemes lacked proper management in terms of training and support [43]. In addition, the large machinery that was being promoted in these schemes were not appropriate for the prevailing farming set-up that is characterised by small and fragmented plots. Hence, the technologies were not fit for purpose. The government-led schemes also failed due to a number of other factors. These include; poor management, poor infrastructure, lack of financial support, inefficient utilisation of tractors, and lack of incentives for tractor operators to work extended hours [44]. As a result, smallholder traditional grain producers in Zimbabwe use manual production methods due to lack of appropriate mechanisation technologies meeting their needs [18].

Promotion and implementation of agricultural mechanisation needs a properly crafted strategy, or else it will fail as evident in the failed efforts to mechanise agricultural production by African governments between 1960 and 1970 due to capacity constraints [37]. Implementation of mechanisation is an evolutionary process influenced by a set of factors. Specific agro-climatic factors, social conditions, economic factors and government policy are some of the important factors to consider for successful implementation of agricultural mechanisation [45].

Due to their poor resource endowment, mechanisation solutions could be out-of-reach for most smallholder farmers under the traditional approach of individual ownership. In sub-Saharan Africa, most farmers cannot afford to individually own and operate equipment. Financial support through subsidies or finance schemes are limited with lines of credit being scarce because of lack of eligible collateral [46]. To curb these challenges, provision of mechanisation through service-providers or farmer groups rather than individual farmers was promoted [46]. Tufa et al. [44] and Ngoma et al. [47] concluded that in general smallholder famers are willing to pay to access mechanisation services showing that the mechanisation service provision model is bearing fruit.

6. Farm power options

6.1. Overview

Power is needed on the farm for operating different tools, implements, equipment and during various farm operations [48]. The power can be derived from different sources depending on the nature of the operation to be undertaken, scale and affordability. There are two classes of farm power namely: tractive or mobile power and stationery power. Tractive power is used for operations like land preparation, harvesting and transport whilst stationary power is used for operations like threshing, grinding, and winnowing [37,38]. The power for use in agricultural operations can be derived from different sources which are human power, draught animal power (DAP) and mechanical power [48]. Each of these power sources has its own advantages and disadvantages depending on the application environment. Farm power options can be utilized solely or in combination and the choice of which options to use depends on the type of operation to be undertaken, available time, available alternatives and the associated relative costs [40]. There exists a close connection between availability of farm power and crop productivity [49,50]. The amount of farm power available determines the extent of mechanisation that can be put in place. It is recommended that a power-area ratio of 0.5 hp/ha be maintained or exceeded to effectively increase crop production [51]. Availability of adequate farm power is crucial for timely operations in increasing production and productivity, and improving crop handling to reduce losses [49]. Following, is a detailed discussion of the different power sources available to smallholder farmers for crop production and harvesting in Zimbabwe.

6.2. Human power

Human beings are the main source of power for operating small tools and implements in undertaking agricultural production operations globally [52]. Human powered tools are the most important tools for smallholder farmers in sub-Saharan Africa as they are widely used in crop production [53]. Manual labour lack timeliness of operations and is limited in terms of the amount of land that can be worked. The poor timeliness results in delayed operations, which negatively affects yields whilst small area coverage negatively affects the level of production. The average amount of power that can be derived from humans, classified as men, women and children is 0.06 kW, 0.048 kW and 0.03 kW respectively [48]. Human power is highly versatile and is suitable for all operations at any stage of agricultural production. Human labour is, however, more suited for control-intensive operations that require human judgement such as weeding than power-intensive operations like land preparation and threshing [54]. The availability of human power on agricultural farms is often influenced by the demand for labour from other sectors of the economy [54]. As the labour-force shift towards the secondary and tertiary industries in a developing economy, the primary industry, for example agriculture, suffers labour-deficits. In a developing country like Zimbabwe, it is clear that growth of the secondary and tertiary industries will attract labour from agricultural farms leaving them vulnerable.

Areas facing labour shortages due to rural-urban migration can make use of farm machines to enhance crop productivity and production [55]. It can be seen from the Japan scenario that shortages in farm labour can be met by introduction of farm mechanisation systems. In Japan, cultivators became more relevant during the late 1950s due to shifting of labour from farms to industries in response to rapid post war industrialization. Further shifts of labour influenced the development of rice transplanters and harvest combines in the late 1970s in Japan [54]. The majority of Zimbabwean smallholder farmers depend on rain-fed agriculture and timeliness of operations is critical in optimizing the use of rain water but there is generally a shortage of labour on these farms. This is because more than 85 % of farm-workers were displaced during the period of the land reform programme [56].The new farmer-owners cannot afford to pay the desired wage which is on average USD 3 [56] to the remaining farm workers. The underpaid farm-workers eventually leave the farms in search of other ventures with better income levels [57]. Rural-urban migration has created labour deficit in African farms leading to a rise in labour wages and consequently production costs [37]. In response to raising wages, farmers have resorted to use of family labour but with a compromise on area under production to small manageable areas [37].

Despite the shortfalls of human labour as a source of power, it still dominates crop production operations. In Zimbabwe it is used during all production stages from land preparation to harvesting. Most hand tools that make use of human power, for example, hoes are affordable and can easily be accessed by most farmers. In India, one of the world's largest mechanisation equipment and machinery manufacturer, advanced products are abundantly available on the markets but human labour still dominate production systems of some crops.

6.3. Draught animal power

Draught animal power (DAP) is a reliable and popular source of farm power in most developing countries [58] and it has been a successful mechanisation innovation in sub-Saharan Africa [36]. Smallholder farmers in Zimbabwe rely heavily on animal power for primary tillage and crop establishment operations [59]. In Zimbabwe, DAP is commonly derived from oxen and donkeys. The amount of power produced by the animals is a proportion of their body weight [48]. For oxen, 10–14 % of the body weight is the equivalent draught force produced whilst for donkeys it is 32–36 % of the body weight [48].

DAP is generally available to most smallholder farmers and can result in a relative increase in the efficiency and productivity than manual based systems [55]. The use of animal power offers better work rates, expansion of area under production and higher crops yields at large scale compared to manual power systems [60]. A DAP-based crop establishment kit could cost USD 1750, the same amount it costs to acquire a 2WT-based kit [33]. However, due to the low capacity of the DAP-based system, the 2WT-based kit is more cost-effective under the same operating conditions.

The farming systems in the smallholder farming sector of Zimbabwe are mainly based on integrated crop and livestock production [61]. There is a synergistic relationship between livestock production and crop production. Livestock provide draught power to facilitate tillage, planting and weeding operations while supplying organic manure to enhance soil nutrition at low cost whilst crops provide feed to livestock in the dry season [61]. These synergistic benefits of the existence of livestock on farms are often rarely fully realised by smallholder farmers in Zimbabwe. This is mainly because the manure produced is of low quality and is insufficient to provide the required soil nutrients to meet the crop nutritional requirements, while the harvested crop stover is insufficient to provide feed for the livestock with draught animal power being limited to the provision of power in agricultural operations [61].

DAP is not a common resource for all farmers in Zimbabwe. Farmers with limited access to resources cannot afford DAP and resort to manual labour for farm operations even for power-intensive operations like primary tillage [62]. Some farmers without access to DAP are forced to venture into conservation agriculture practices like basin planting using manual labour [62].

On the other hand, compared with motorised systems, animal power systems are characterized by low work rates, high levels of drudgery and high labour requirements but their performance is better than that of human powered systems. To ensure timeliness of operations, allocating one pair of draught animals to an area between 1.5 and 2.5 ha is reasonable on net area basis [58]. Most smallholder farmers in Zimbabwe cultivate land that is within the recommended command area and this could be the reason why the DAP technology has been successful. The cost of acquiring and maintaining DAP-based equipment is relatively low and most farmers that afford to keep the animals can afford to acquire and maintain the equipment. However, the cost of animal power include the cost of raising, training and maintaining the animals [39,51]. The amount expended towards meeting these costs is more than the amount generated or saved through the use of animal power in farm operations which makes this option cost-ineffective. Sustainable use of DAP is influenced by tsetsefly infestation which is endemic in some parts of Zimbabwe and capacity to control ticks that spread diseases [63].

Although draught animals have been playing an essential role in agricultural production worldwide, in recent decades there has been a trend towards replacing draft animals with farm machines [55]. With increases in food demand, production is expected to increase which could mean an increase in cultivated area, number of animal pairs and labour required. Intensification of agricultural production also requires that operations are done precisely and animal draught technologies cannot meet that demand.

6.4. Motorised power

Motorised power is derived from diesel and petrol engines, tractors and self-propelled machines [58]. Tractors and self-propelled machines provide tractive power whilst electric motors and diesel engines provide stationary power for operations like milling and threshing. Proper use of motorised power in agricultural production increases productivity, improve the quality of produce and increase the total area under production [64]. Mechanisation of the farming activities has been introduced in the rainfed sector as a strategy to improve productivity. For instance, mechanisation of farm operations is found to be the main source for increasing the efficiency of rice cultivation among smallholder farmers in Kenya [65]. Use of motorised power reduces the demand for DAP. A 1 % increase in use of motorised mechanisation in China reduced the demand for DAP by 2.8 % in the long run, but no effect was noted in the short run [55]. Traditionally, draught animals have played an essential role in agricultural production in many countries but the introduction of motorised mechanisation resulted in a decrease in demand for animal draught power for example in India and China [55].

There is generally a shortage of motorised power for field operations in Zimbabwe. Only 2 %–15 % of the total land cultivated in Zimbabwe is prepared using tractors with DAP dominating land preparation being responsible of preparing 70 %–90 % of the land [40]. The main reason for this is that the majority of Zimbabwean farmers cannot access the available motorised power options like four wheel tractors (4WTs) and their respective attachments. In addition, large combine harvesters are beyond the reach of smallholder farmers because they are expensive and do not match well with their production systems and small and fragmented arable land [66].

The majority of owners of combine harvesters in Zimbabwe are largescale farmers who then hire out services to medium-scale and small-scale farmers who can afford the services [66]. This model has worked well in India [67] but its success in most African countries with smallholder farmer dominated agricultural sectors is yet to be systematically reviewed. This is because the smallholder farms are small, separated and dispersed which increase the operational costs [52,58]. Because of their lower cost (procurement and operational) compared to large tractors and their ability to be fully utilized on small farm [67], two-wheel tractors (2WT) can be a better motorised power option for smallholder farming systems in Zimbabwe.

Bangladesh's success in farm mechanisation was fueled by a model that promoted use of small machines for example 2WTs by smallholder farmers [68]. The 2WTs are a cheap and reliable source of motorised power, cheaper than draught power and almost every famer has access to its services in Bangladesh [68]. A model whereby farmers hire small mechanisation services from service-providers and do not have to own their own equipment have allowed even the poorest farmer in Bangladesh to access mechanisation [68]. Since both Bangladesh and Zimbabwe have similar agricultural setups i.e. smallholder farmer dominated, the service-provider-based mechanisation strategy could also work for Zimbabwe. Smallholder farmers in Zimbabwe can be classified as communal areas, A1 farms and old resettlement farms [66]. Service-provision, however, needs to be adopted with caution as it may not be profitable for all operations posing the risk to send negative impressions. The model could work for harvesting operations but not for ploughing [67]. A pair of conservation agriculture-based planters coupled to a 2WT have capacity to establish at least 80 ha of sorghum crop per year assuming a 30-day window period for planting from rain onset. Given that the maximum arable land area under the smallholder farmer setting is 10 ha, the kit can be used to plant by at least 8 farmers. Two-wheel tractors are, however, limited to less power intensive operations like conservation tillage and does not support deep tillage operations where four wheel tractors prevail.

With an initial investment of about USD 1750, a service provider or any other potential owner can acquire a 2WT-powered CA-based direct seeding kit [33]. This amount is reasonable for private players that may want to offer planting services to farmers. At 20 % profit margin, the service-provider can then offer mechanised planting services to farmers at about USD 45 per ha. The service price will not only allow farmers to pay less compared to using animal-drawn plough and manual power to establish the crop, but to also enjoy the improved yields that come with mechanised planting and the peace of mind of not worrying about machinery ownership, operation, repair and maintenance.

6.5. Environmental impact

The utilisation of these power options to conduct agricultural operations releases some greenhouse gasses (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the atmosphere, resulting in global warming and climate change which negatively affect agricultural production [69,70]. The GHG emission sources for DAP include N_2O and CH_4 from manure management, N_2O from excreta deposited in grassland and cropland, CH4 from rumination processes, as well as GHG emissions from feed production and animal breeding operations [71]. For motorised power, the sources of emissions include machinery manufacture and maintenance, fuel combustion, and fuel production and transportation emissions [71]. The emission levels for DAP are lower than those of motorised power when using 4WTs [72]. However, DAP emissions are higher than those of motorised power when using 2WTs [72]. Most GHG emissions from motorised power come from the combustion of fuels [71], hence migrating from bigger 4WTs to smaller 2WTs with lesser fuel consumption rates is expected to significantly reduce the GHG emissions from motorised power. Further, adoption of CA, which eliminates primary and secondary tillage operations require less energy which makes it possible to integrate renewable energy sources such as solar energy to the machinery. The applicability of electric tractors [73,74] in CA-based traditional grain production systems is still a virgin area, especially in developing countries and therefore require further investigation.

7. Field production operations

This section discusses the field operations that are undertaken during traditional grain production from land preparation to harvesting.

7.1. Tillage and crop establishment

Conventional tillage in Zimbabwe entails cutting and turning the soil burying the weeds and crop residues to ensure that crops germinate in a relatively weed free environment [59]. Conventional traditional grain production requires that land is ploughed to a depth of 30 cm using hand hoes, animal-drawn mouldboard ploughs or tractor-mounted reversible mouldboard or disc ploughs [75]. Smallholder farmers in semi–arid Zimbabwe rely heavily on DAP and ox-drawn mouldboard ploughs for primary tillage and crop establishment [59]. Conventional tillage has been criticised for failure to reduce the effects of dry spells on crops and to combat soil loss being caused by water erosion [59]. Direct seeding under conservation agriculture has emerged as an alternative to the labour-intensive, water-intensive and energy-intensive transplanting method in rice production systems in South Asia [76].

Seed drills are better than broadcasting when establishing a traditional grain crop. This is because they ensure good seed to soil contact, promote rapid germination and results in more uniform and optimum crop stands [77]. Drills are compatible with conventional, reduced and no-till tillage systems. They allow crops to be planted in rows at the desired inter-row spacing but for plants that require a specific in row spacing like traditional grains, thinning to recommend in-row spacing is required. Commercial producers of traditional grains who are well resourced use seed drills for crop establishment but the technology is not accessible to smallholder farmers who rely mostly on the mouldboard plough for tillage and ploughing.

Seedling transplanting from nurseries is usually used in rice cultivation and in the production of vegetable crops [78] but it has been adopted by smallholder farmers in Zimbabwe to establish sorghum and millet crops [79] and is commonly done manually [63,64]. Even though transplanting is characterised by high crop yields and less weed infestation, it is labour-intensive when performed manually [80] which makes it inapplicable on large areas. Compared to mechanical transplanting methods which have labour requirements of 3 man-days per hectare, manual transplanting methods have labour requirements of about 33 man-days per hectare and timeliness rates of 0.04 ha/day [80]. Generally, establishing crops by transplanting is labour intensive and time consuming. Labour and time is also required before field transplanting to monitor the nurseries [79]. For rain-fed systems, manual transplanting is only suitable for small production areas because of its high labour demand and poor timeliness nature [78].

7.2. Weed control

Weeds are a major problem in field crop production and can reduce yields by at least 20 % [81]. It is necessary to keep weed population below its threshold so that crop yields will not be affected [82]. Sorghum producers in Zimbabwe use manual, mechanical and chemical methods to control weeds, with manual weeding using hoes considered the dominant method used [81]. Hand weeding using hoes is slow, arduous and labour intensive. During the weeding period, farmers spend 75 % of their time battling with weeds in their sorghum fields [81]. The widespread hand-weeding in Zimbabwean field crop production systems is one of the major setbacks to the adoption of conservation agriculture in the field crop productions systems [83].

Conventionally, animal-drawn ploughs and cultivators are used to perform inter-row weed control [59]. Ox-drawn mouldboard ploughs and ridgers control weeds by removing weeds between the rows and burying weeds along the row [84]. Tractor-powered soil engaging equipment that can be used for weed control include the duck foot field cultivator, one way disk, spring-tooth cultivator, and a rotary hoe [85]. These manual, animal drawn and tractor-powered options for weed control are time-saving and less labour-intensive but are characterized by extensive soil disturbance which contradict with the principles of conservation agriculture which are being advocated for towards achieving sustainable crop production.

Use of herbicides has been found to be effective in reducing the time and labour required in weed control [65,86]. For herbicides to be effective, their application must be done uniformly, using the correct technique and recommended application rates [87]. Herbicides can be applied in a variety of forms; for example liquids, granules and fumigation and a variety of equipment have been developed over time to apply these forms [88]. Application methods can be grouped as: (i) broadcast methods, where application is done to the entire area under treatment and (ii) direct application methods where application targets the unwanted crops [87]. Knapsack sprayers, boom sprayers and spray guns can be used under broadcast application whilst wick applicators, single nozzle knapsack sprayers and gun sprayers with narrow orifice disks are used for direct application. Direct methods of herbicide application avoids herbicide drift and minimizes the risk of environmental contamination and damage of non-target organisms [88]. There are, however, some drawbacks in the use of herbicides which include herbicide resistance and environmental contamination.

Grass mowers can be used to control weeds in row crops. Rotary mowers, flail mowers, reciprocating sickle bar mowers and real mowers can be used to mechanically control weeds in row and tall growing crops [89]. This equipment defoliate the weeds and affect their growth. The efficacy of mowing as a weed control option depends on the frequency of mowing and the type of weed typically classified as either broadleaf or grass weeds [90].

Thermal weed control is one of the most promising methods to control weeds in organic conservation agriculture production systems. Steam, flame, hot water and infrared heaters are some of the methods already exposed to research in the development of equipment for implementation [91]. Thermal weeding equipment is, however, slow, expensive and produces large amounts of carbon dioxide which contributes to global warming [92] and this method is more effective on broad leafed weeds than grasses. The mentioned row weeding systems are limited in terms of their efficiency in weed control since they do not control in-row weeds except for the mouldboard plough and the duck foot ridger. This means that they need to be combined with other weed control methods like hoe weeding, hand weeding or direct herbicide spraying. There is need to combine weed control methods to achieve satisfactory results [84].

7.3. Harvesting

Harvesting of most varieties of millets and sorghum is predominantly done manually using sickles, hand knives, finger knives or scissors [76–78]. Manual harvesting using sickles results in high grain losses, high labour requirements, high levels of drudgery, are slow and contribute to poor grain quality [77,79]. Nikam et al. [93] found a labour requirement of 150 man-hours for manual harvesting compared to 6.8 man-hours for the mechanised system. In some places, complete sorghum harvesting requires that the crop is cut twice, the first cut involves removing the pannicle or the head and while the second one removes the stalk [93]. In some places, the whole crop is cut once at the base [94]. A tractor mechanism with two separate mechanisms for nipping the panicles and cutting the stalk at the bottom can be used for the harvesting method that require two cuttings to keep both fodder and grain [93].

There is evidence of significant research in the development of traditional grain harvesting equipment to suit smallholder farmers in Asia. A tractor front-mounted sorghum harvester that cut and convey the panicles to a collection box as well as cutting and windrowing the stalks was developed in India [93]. To address the challenge of manual harvesting of finger millet [95], walk-behind and ride-on paddy rice harvesters were tested for harvesting finger millet and an efficiency of 95 % was achieved [94]. Commercially available reapers were screened and the Shrachi Taro reaper (Fig. 2) was field-tested. Use of paddy rice harvesters, wheat harvesters and reapers made it possible to mechanise finger millet harvesting in small cultivated areas, reduced labour costs and labour requirements, and facilitated timeous harvesting [94]. However, significant labour is required for gathering and stacking the cut crop awaiting threshing. Dropping stalks on the ground leads to soil contamination of grain.

Generic combine harvesters can also be used for sorghum and millet harvesting [81,82]. Modifications are necessary for this to happen [97], for example, adjusting the rotational speed of the threshing cylinder to speeds between 750 rpm and 1300 rpm [98] and reducing the size of perforations of the screen in the threshing section [99]. Commercial traditional grain farmers in Zimbabwe use combine harvesters but smallholder farmers who constitute the majority, rely heavily on manual harvesting methods which are slow, drudgerous and labour-intensive. Combine harvesters are better in performing grain harvesting operations but are expensive to smallholder farmers [100]. However, there is no evidence of smallholder farmer suitable equipment for harvesting traditional grains on the Zimbabwean market and in most cases farmers are not even aware of their existence.

8. Policy issues

As part of the solutions to addressing the barriers to traditional grain production, mechanisation technologies should be made available [39]. However, to-date, only threshers have improved significantly in terms of numbers available on the local market. Whilst

Fig. 2. The Shrachi Taro reaper: *Source* [96].

planting and harvesting equipment are important in reducing labour demands and improving crop yields and quality of grain, this equipment is not easily available on the Zimbabwean market. There is therefore need for Government of Zimbabwe and stakeholders to develop strategies to make the missing critical technologies available to farmers which can be done through technology imports or local manufacturing. The development of mechanisation for local manufacturing, however, depends on the demand of the technologies by farmers [39]. As such, there is limited demand for mechanisation in Africa and there is much reliance on imported mechanisation technologies which are not designed for local conditions [67]. Importing and promoting mechanisation technologies to stimulate demand whilst reverse engineering imported technologies and developing new designs for local production could be a noble strategy to solving these problems.

The Zimbabwean policy has been focusing on importing large 4WTs and accompanying attachments through various programs to improve the levels of mechanisation [101]. This model of mechanisation has not shown widespread success to date and it could be because the technology is not appropriate for the majority of farmers i.e. small-holder farmers. The small, separated and dispersed farms are not best suited for large machinery [86]. In the past century, mechanisation has been focusing certain groups of farmers and leaving other farmer groups behind [66]. A holistic approach is needed to promote mechanisation and leave no farmer behind. Limited land area in communal areas make the use of tractors difficult [66]. There is need to develop strategies to promote mechanisation at all farmer level with large tractors targeting medium-scale to large-scale farmers whilst small tractors target smallholder farmers. In addition, scale-appropriate equipment will need to be developed and promoted together with the suitable support services (e.g. repair and maintenance, fuel and spare parts), and the related infrastructure. Farmer associations representing smallholder farmers plus other stakeholders need to be consulted to gather perceptions on which mechanisation technologies to prioritise, for which crops as well as the specifications of the machinery.

The mechanisation model in Zimbabwe is based on individual ownership with some resourceful famers hiring out mechanisation services [66]. The cost of acquiring or hiring mechanisation is, however, high because large 4WTs and their attachments form the basis of these models hence most small-scale farmers do not have access. Smallholder farmers can, however, access mechanisation through hiring from service-providers and avoid the burden to purchase, own and maintain equipment and machinery [86]. However, the model of service-provision is still limited in the country.

The Government of Zimbabwe has been on the fore-front with regards supply of mechanisation technologies [57,83]. It is, however, recommended that private sector-driven technology supply models be promoted [67] with government support through creation of a business enabling environment. The responsibility to acquire, repair and maintain as well as operate mechanisation must be fully met by private companies. If this model is to work, Government must encourage free competition amongst private sector and avoid environments that promote creation of monopolies. In addition, entry requirements; for example, operating license fees, must not be deterrent. Incentives, for example, priority in the access of foreign currency and fuel and duty waivers on imported machinery and spare parts, can also be availed to participating companies to oil up operations.

There is a need for various parties to collaborate for sustainable agricultural mechanisation to occur and flourish [45]. Private sector should lead the provision of mechanisation services [45], whilst research and academic institutions lead the research and development of machinery and equipment. Farmer associations could assist by guiding the research and development processes through provision of information on farmer needs to ensure development of adoptable machinery and equipment. International research and development organisations could assist by mobilizing funding resources to the tooling within the equipment manufacturing industry to meet international standards. Activities like research and development as well as technology promotion and awareness as led by research institutions and farmer associations respectively, to stimulate demand for mechanisation, can also be funded by international organisations.

Some of the stakeholders have already been participating in these activities in Zimbabwe but doing so in isolation. There is lack of a coordination mechanism or framework to combine the outputs of the individual efforts in a synergistic manner. The key driver for widespread adoption of traditional grain production is the economic viability of the value chain. Promoting use of mechanisation in isolation without considering market linkages, access to credit and other inputs like fertiliser and seed will not bring forth economic viability. There is a need to setup a forum comprising of all stakeholders involved in the traditional grain value chain to work on how the value chain can be made profitable for all players.

9. Conclusions

In conclusion, the 2WT is a better power source option for smallholder traditional grain producers whilst the large 4WT can be suitable for large-scale traditional grain farmers considering issues of resource-endowment and land area under production. Both small and large-scale producers are encouraged to practice direct-seeding under conservation agriculture in their production systems. There is therefore need to develop mechanisation equipment such as no-till direct seeders that support the initiative. The no-till direct seeders will allow minimum soil disturbance and permanent soil cover to be achieved.

It has been established that chemical weed control is the most efficient method to control weeds. However, considering that they are a human and environmental hazard, there is need to further develop other control methods like mowing and bio-pesticides and develop equipment and machinery that support easy and cost-effective implementation of such technologies. These methods have a potential to effectively support production of traditional grains under conservation agriculture as they support minimum soil disturbance, permanent soil cover and enhanced biodiversity. However, the efficacy and sustainability of these weed control methods is seldom known which warrants the need for further research in terms of weeding frequency as well as optimum concentration and mode of application in the case of bio-pesticides. In terms of harvesting, mini combines should be developed for smallholder farmers whilst existing combines can be utilized by large-scale farmers subject to performing the necessary adjustments to accommodate traditional grains.

10. Recommendations

Based on the review, the following recommendations are proposed.

10.1. Farmer support

- Encourage private companies to establish equipment leasing services targeted at smallholder farmers to reduce the financial burden of ownership.
- Consult farmers and farmer associations on which operations to prioritise, machinery and equipment preferences as well as mechanisation training programs to implement.
- Encourage non-governmental organisations, development partners and private sector to fund incentive packages for traditional grain farmers willing to use mechanisation in their farming operations. These can be in the form of free or subsidised selected inputs.

10.2. Infrastructure and skills development

- Improve the existing and avail new support infrastructure; for example, roads, fuel stations and hardware shops for spare parts.
- Train local artisans and local mechanics to provide repair and maintenance services.
- Train and capacitate extension staff to raise awareness on the advantages of mechanisation in agricultural production within the farming community to promote adoption.

10.3. Monitoring and evaluation

- Establish and fund a monitoring and evaluation framework to track progress and make adjustments as needed.

10.4. Research and development

- Research institutions should focus on developing low-cost, durable mechanisation solutions as well as cost-effective and sustainable weed management strategies tailored to the specific needs of Zimbabwean farmers.
- Encourage the issuance of grants by Government and development partners to research and academic institutions as well as postgraduate students at local institutions. The grants can be used to equip workshops and laboratories at academic and national research institutions to enhance the research environment and improve the quality of research output. Private sector can then pilot or commercialise the research utilising funding provided by local banks and other financial institutions.
- Reverse-engineer imported mechanisation equipment for customisation and to accelerate the development and manufacturing processes.
- Facilitate participatory testing of mechanisation equipment under different farm operating conditions to ensure equipment is fit-for-purpose and to enhance adoption or further modification.

10.5. Policy and regulation

- Setup a taskforce comprising of experts in the key traditional grain value chain areas to work on mechanisms to make the value chain viable. Government can take a lead role by coordinating and funding some of the activities of this taskforce. A budget from treasury can be set aside for funding purposes and periodic progress review meetings must be held to assess progress and challenges that might arise.
- Develop comprehensive value chain programs that include mechanisation, market access, credit facilities, and input supplies to ensure the economic sustainability of traditional grain production.
- Implement policies that require performance tests and quality certification of both imported and locally-produced equipment to be conducted before entering the market space to ensure only quality products enter the market. Selling poor quality products could tarnish the image of the mechanisation discipline and can cause non-adoption.
- Implement policies that reduce import duties on small-scale farming equipment and provide subsidies for local manufacturing.
- Develop an Intellectual Property policy that ensures fair rewards for all parties involved in research and development of mechanisation technologies, based on contribution. This encourages researchers to engage in meaningful development of relevant mechanisation technologies.
- Put in place legislation that govern the operation of 2WTs in Zimbabwe. This entails recognition of 2WTs as a type of vehicle and issuance of driver's licences to its operators. The protocol for issuance could follow the one for class 5 driver's licences issued to 4WT drivers. Legislation should make it mandatory for 2WT operators to wear a helmet and knee and elbow pads, with failure of compliance resolved as guided by class 3 (motorcycle driver's license) guidelines. All 2WT found on Zimbabwean roads must have head and tail lamps.

Funding

Financial support to this research was provided by the Ministry of Higher and Tertiary Education, Innovation, Science and Technology Development, through the University of Zimbabwe Vice Chancellor's Challenge Research Fund.

Data availability statement

No data was used for the research described in the article.

CRediT authorship contribution statement

Tinashe Madzivanzira: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Brighton M. Mvumi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Raymond M. Nazare:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Elijah Nyakudya:** Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Florence Mtambanengwe:** Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Paul Mapfumo:** Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Paul Mapfumo reports financial support, administrative support, and travel were provided by Zimbabwe Ministry of Higher and Tertiary Education Innovation Science and Technology Development. Paul Mapfumo, Florence Mtambanengwe, Elijah Nyakudya, Raymond Nazare reports a relationship with University of Zimbabwe that includes: employment. Brighton Mvumi reports a relationship with University of Zimbabwe that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to acknowledge support from the University of Zimbabwe Innovation Hub and the Future Grains for Africa Programme as well as technical help from the Department of Agricultural and Biosystems Engineering.

References

[1] African Development Bank, African economic outlook: Zimbabwe (2018) 1–10, https://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-Documents/country_notes/Zimbabwe_country_note.pdf, 2018.
[2] Zimstat, Zimbabwe Smallholder Agricultural Productivity Survey 2017 Report, 2019, pp. 1–50.
[3] A.A. Maiyaki, Zimbabwes agricultural industry, Afr. J. Bus. Manag. 4 (2010) 4159–4166.
[4] E. Dirk, Grain and feed annual: Zimbabwe. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=GrainandFeedAnnual_Pretoria_Zimbabwe_06-17-2021.pdf, 2021.
[5] A.M. Manjera, P. Siwadi, M. Twum-Darko, Socio-economic factors influencing usage ofclimate driven seed maize in Zimbabwe, Asian J. Agric. Extension, Econ. Sociol. 39 (2021) 336–348, https://doi.org/10.9734/ajaees/2021/v39i1030700.
[6] SEEDCO, SC513, 2021. https://www.seedcogroup.com/zw/products/maize/early-maturing-hybrid/sc-513#:~:text=Elasticmaizehybrid%2Cgoodfor,upto10t%2Fha. (Accessed 18 October 2022).
[7] Seed Co, Farmer's Guide: Grain Crops, Farmer's Guid, 2018. http://www.seedcogroup.com/sites/default/files/AgronomyManual.pdf. (Accessed 10 June 2024).
[8] H. Tibugari, T. Chikasha, N. Manyeruke, N. Mathema, J.P. Musara, D. Dlamini, R. Mapuranga, O. Mapanje, A. Banda, C. Parwada, Poor maize productivity in Zimbabwe: can collusion in pricing by seed houses be the cause? Cogent Food Agric. 5 (2019) https://doi.org/10.1080/23311932.2019.1682230.
[9] J. Basera, An Assessment of Smallholder Maize Productivity and Profitability in Zimbabwe: A Case of Mazowe District, Esami Business School, 2015, https://doi.org/10.13140/RG.2.1.2192.6647.
[10] M. Moyo, B.M. Mvumi, M. Kunzekweguta, K. Mazvimavi, P. Craufurd, Farmer perceptions on climate change and variability in semi-arid Zimbabwe in relation to climatology evidence, African Crop Sci. Soc. 20 (2012) 317–335. https://www.ajol.info/index.php/acsj/article/view/81753.
[11] K. Mulungu, J.N. Ng'ombe, Climate change impacts on sustainable maize production in sub-Saharan Africa, A Review (2019) 13, https://doi.org/10.5772/intechopen.90033.
[12] D. Gumbo, M. Wuta, I. Nyagumbo, Dead level contour technical design parameters required for sustainable crop production in semi-arid areas of Zimbabwe, Discov. Sustain. 2 (2021), https://doi.org/10.1007/s43621-021-00032-z.
[13] V.T. Mutekwa, Climate change impacts and adaptation in the agricultural sector: the case of smallholder farmers in Zimbabwe, J. Sustain. Dev. Afr. 11 (2009) 237–256.
[14] J. Mukarati, J. Zivanomoyo, P. Gutu, The economic impacts of climate change on maize production in Zimbabwe, Res. J. Econ. Manag. Stud. 1 (2021) 1–9. http://ir.gzu.ac.zw:8080/xmlui/bitstream/handle/123456789/446/TheEconomicImpactsofClimateChangeonMaizeProductioninZimbabwe.pdf?sequence=1&isAllowed=y.
[15] T. Muzerengi, H.M. Tirivangasi, Small grain production as an adaptive strategy to climate change in Mangwe District, Matabeleland South in Zimbabwe, Jàmbá J. Disaster Risk Stud. 11 (2019) 1–9, https://doi.org/10.4102/jamba.v11i1.652.
[16] S. Chamunorwa, N. Sakadzo, T.A. Kugedera, Exploring constraints and opportunities for sorghum production in dry regions of Zimbabwe, NASS J. Agric. Sci. 3 (2021) 1–7, https://doi.org/10.36956/njas.v3i2.327.
[17] M. Svodziwa, The feasibility of small grains as an adoptive strategy to climate change, Russ. J. Agric. Socio-Economic Sci. 41 (2015) 40–55, https://doi.org/10.18551/rjoas.2015-05.04.

[18] UNDP, Barrier Analysis of Small Grains Value Chain in Zimbabwe, 2018. http://www.zrbf.co.zw/data/media/00001062/ZRBF-Barrier-Analysis-of-Small-Grains.pdf.
[19] K. Phiri, T. Dube, P. Moyo, C. Ncube, S. Ndlovu, Small grains "resistance"? Making sense of Zimbabwean smallholder farmers' cropping choices and patterns within a climate change context, Cogent Soc. Sci. 5 (2019) 1–13, https://doi.org/10.1080/23311886.2019.1622485.
[20] Mukarumbwa. P., Mushunje. A., Potential of sorghum and finger millet to enhance household food Security in Zimbabwe's semi-arid regions : A Review, Jt. AAAE Third Conf. 48th AEASA Conf. Sept. 19 - 23, 2010, Cape Town, 2010, pp. 1–23. https://doi.org/10.22004/ag.econ.96430.
[21] B. Chazovachii, A. Chigwenya, A. Mushuku, Adoption of climate resilient rural livelihoods through growing of small grains in Munyaradzi communal area, Gutu district, Afr. J. Agric. Res. 7 (2012) 1335–1345, https://doi.org/10.5897/AJAR10.921.
[22] C. Mutami, Smallholder agriculture production in Zimbabwe: a survey, cons, J. Sustain. Dev. 14 (2015) 140–157, https://doi.org/10.7916/D8F47NV5.
[23] Y. Xiong, P. Zhang, R.D. Warner, Z. Fang, Sorghum grain: from genotype, nutrition, and phenolic profile to its health benefits and food applications, Compr. Rev. Food Sci. Food Saf. 18 (2019) 2025–2046, https://doi.org/10.1111/1541-4337.12506.
[24] H.H. Al Mamari, Phenolic compounds: classification, chemistry, and updated techniques of analysis and synthesis, in: F.A. Badria (Ed.), Phenolic Compd. - Chem. Synth. Divers. Non-conventional Ind. Pharm. Ther. Appl., IntechOpen, Rijeka, 2022, https://doi.org/10.5772/intechopen.98958.
[25] M. Rahman, S. Rahaman, R. Islam, F. Rahman, F.M. Mithi, T. Alqahtani, M.A. Almikhlafi, S.Q. Alghamdi, A.S. Alruwaili, S. Hossain, M. Ahmed, R. Das, T. Bin Emran, S. Uddin, Role of phenolic compounds in human disease : current, Molecules 27 (2022) 1–36.
[26] S. Puranik, J. Kam, P.P. Sahu, R. Yadav, R.K. Srivastava, H. Ojulong, R. Yadav, Harnessing finger millet to combat calcium deficiency in humans: challenges and prospects, Front. Plant Sci. 8 (2017) 1–16, https://doi.org/10.3389/fpls.2017.01311.
[27] A. Orr, C. Mwema, A. Gierend, S. Nedumaran, Sorghum and millets in eastern and Southern Africa : facts, trends and outlook. http://oar.icrisat.org/9441/, 2016.
[28] M. Debieu, B. Sine, S. Passot, A. Grondin, A.E. Akata, P. Gangashetty, V. Vadez, P. Gantet, D. Foncéka, L. Cournac, C.T. Hash, N.A. Kane, Y. Vigouroux, L. Laplaze, Response to early drought stress and identification of QTLs controlling biomass production under drought in pearl millet, PLoS One 13 (2018) 1–19, https://doi.org/10.1371/journal.pone.0201635.
[29] R. Krishnan, M.S. Meera, Pearl millet minerals: effect of processing on bioaccessibility, J. Food Sci. Technol. 55 (2018) 3362–3372, https://doi.org/10.1007/s13197-018-3305-9.
[30] V.A.V. Queiroz, P.E.O. Guimarães, L.R. Queiroz, E.O. Guedes, V.D.B. Vasconcelos, L.J. Guimarães, P.E.A. Ribeiro, R.E. Schaffert, Iron and zinc availability in maize lines, Ciênc. Tecnol. Aliment. Campinas 31 (2011) 577–583.
[31] J.P. Musara, L. Musemwa, A. Mushunje, M. Mutenje, C. Pfukwa, Sorghum value chain analysis in semi-arid Zimbabwe, South African J, Agric. Ext. 47 (2019) 164–178, https://doi.org/10.17159/2413-3221/2019/v47n1a497.
[32] I. Kutyauripo, P. Mutombo, Determinants of production of sorghum (sorghum bicolor) and millet (Eleusine coracana) in Zvimba district of Zimbabwe, Int. J. Sci. Res. Multidiscip. Stud. 6 (2020) 37–42. www.isroset.org.
[33] Giving Power to Smallholders in Nyanga District, n.d. https://knowledgeplatform.hellotractor.com/wp-content/uploads/2020/02/Factsheet-Zimbabwe.pdf.
[34] H.D.J. van Heemst, Crop calendar, workability and labour requirements, (n.d.) 251–262. https://library.wur.nl/WebQuery/wurpubs/fulltext/172074 (accessed June 10, 2021).
[35] AMA, Weekly commodity market bulletin, Harare, https://ama.co.zw/wp-content/uploads/2022/09/Bulletin-Number-36-of-2022.pdf, 2022.
[36] E. Anthony, M.S. Mwangi, Mechanization policy in sub-Saharan Africa: a review of challenges and opportunities. https://www.academia.edu/1497132/MECHANISATION_POLICY_IN_SUB_SAHARAN_AFRICA_A_REVIEW_OF_CHALLENGES_AND_OPPORTUNITIES, 2012.
[37] T. Daum, R. Birner, Agricultural mechanization in Africa: myths, realities and an emerging research agenda, Glob. Food Sec. 26 (2020) 1–10, https://doi.org/10.1016/j.gfs.2020.100393.
[38] O. Srisompun, T. Athipanyakul, S. Isvilanonda, The adoption of mechanization, labour productivity and household income: evidence from rice production in Thailand, Hannover. https://www.econstor.eu/bitstream/10419/208384/1/1683817613.pdf, 2019.
[39] UNDP, Emerging Solutions in Small Grains Value Chains in Zimbabwe, 2018. Harare, http://www.zrbf.co.zw/data/media/00001448/Emerging-Solutions-in-Small-Grains-Chains-in-Zimbabwe.pdf.
[40] F. Chisango, O. Ajuruchukwu, Efficiency effects Zimbabwe ' s agricultural mechanization and fast track land reform programme : a stochastic frontier approach, in: Poster Present. Jt. 3rd African Assoc. Agric. Econ. 48th Agric. Econ. Assoc. South Africa Conf., 2010. Agricultural mechanization in Zimbabwe.pdf Cape Town.
[41] J.B. Aune, A. Coulibaly, K. Woumou, Intensification of dryland farming in Mali through mechanisation of sowing, fertiliser application and weeding, Arch. Agron Soil Sci. 65 (2019) 400–410, https://doi.org/10.1080/03650340.2018.1505042.
[42] A.I.M. Nourou, A.K. Saidou, W. Arifa, A.O. Abdoulaye, J.B. Aune, Intensification of pearl millet production in Niger through mechanized sowing and weeding, seed priming, seed treatment, and microdosing, Agronomy 10 (2020) 1–12, https://doi.org/10.3390/agronomy10050629.
[43] G.C. Mrema, S. Miranda-da-Cruz, Agricultural Mechanization in Africa, Time for action, 2008. Vienna, https://www.fao.org/4/k2584e/k2584e.pdf.
[44] A. Tufa, A. Alene, H. Ngoma, P. Marenya, J. Manda, M.A. Matin, C. Thierfelder, D. Chikoye, Willingness to pay for agricultural mechanization services by smallholder farmers in Malawi, Agribusiness 40 (2024) 248–276, https://doi.org/10.1002/agr.21841.
[45] B. Sims, J. Kienzle, Sustainable agricultural mechanization for smallholders: what is it and how can we implement it? Agriculture 7 (2017) https://doi.org/10.3390/agriculture7060050.
[46] J. Van Loon, L. Woltering, T.J. Krupnik, F. Baudron, M. Boa, B. Govaerts, Scaling agricultural mechanization services in smallholder farming systems: case studies from sub-Saharan Africa, South Asia, and Latin America, Agric. Syst. 180 (2020) 1–13, https://doi.org/10.1016/j.agsy.2020.102792.
[47] H. Ngoma, P. Marenya, A. Tufa, A. Alene, L. Chipindu, M.A. Matin, C. Thierfelder, D. Chikoye, Smallholder farmers' willingness to pay for two-wheel tractor-based mechanisation services in Zambia and Zimbabwe, J. Int. Dev. 35 (2023) 2107–2128, https://doi.org/10.1002/jid.3767.
[48] N.S.L. Srivastava, Farm Power Sources , their Availability and Future Requirements to Sustain Agricultural Production, (n.d.) 57–68. https://citeseerx.ist.psu.edu/pdf/15d42792f215f64f3e9d11be158d1b5de0e5bb0b.
[49] S. Singh, R.S. Singh, S.P. Singh, Farm power availability and agriculture production scenario in India, Agric. Eng. Today 34 (2010) 9–20.
[50] P.K. Sundram, B. Sarkar, P. Jeet, S.K. Patel, A.P. Anurag, A. Upadhyaya, B. Bhatt, Dynamics of farm power sources and their availability in Bihar, J. AgriSearch 7 (2020) 128–131, https://doi.org/10.21921/jas.v7i03.18685.
[51] S.O. Nkakini, M.J. Ayotamuno, S.O.T. Ogaji, S.D. Probert, Farm mechanization leading to more effective energy-utilizations for cassava and yam cultivations in Rivers State, Nigeria, Appl. Energy 83 (2006) 1317–1325, https://doi.org/10.1016/j.apenergy.2006.03.001.
[52] Sources of Farm Power, 2001. https://ccsuniversity.ac.in/bridge-library/pdf/Lecture-2-Sources-of-farm-power.pdf.
[53] B.G. Sims, J. Kienzle, Farm power and mechanization for small farms in sub-Saharan Africa. https://www.fao.org/publications/card/en/c/6e76ecd0-1097-588c-ab99-7c5d29a6d055/, 2006.
[54] P. Pingali, Agricultural mechanization: adoption patterns and economic impact, in: R. Evenson, P. Pingali (Eds.), Handb, Agric. Econ., 2007, pp. 2779–2805, https://doi.org/10.1016/S1574-0072(06)03054-4.
[55] X. Zhou, W. Ma, G. Li, Draft animals, farm machines and sustainable agricultural production: insight from China, Sustain. Times 10 (2018) 1–16, https://doi.org/10.3390/su10093015.
[56] I. Scoones, B. Mavedzenge, F. Murimbarimba, C. Sukume, Labour after Land Reform : the Precarious Livelihoods of Former Farmworkers in Zimbabwe, vol. 50, 2018, pp. 805–835, https://doi.org/10.1111/dech.12449.
[57] Zimbabwe Reliefweb, Farm labour shortage threatens food production. https://reliefweb.int/report/zimbabwe/zimbabwe-farm-labour-shortage-threatens-food-production, 2009. (Accessed 10 March 2021).
[58] S.K. Lohan, M.K. Narang, G.S. Manes, N. Grover, Farm power availability for sustainable agriculture development in Punjab state of India, Int. Agric. Eng. J. 17 (2015) 196–207.

[59] I.W. Nyakudya, L. Stroosnijder, Conservation tillage of rainfed maize in semi-arid Zimbabwe: a review, Soil Tillage Res. 145 (2015) 184–197, https://doi.org/10.1016/j.still.2014.09.003.
[60] P.M. Guthiga, J.T. Karugia, R.A. Nyikal, Does use of draft animal power increase economic efficiency of smallholder farms in Kenya? Renew. Agric. Food Syst. 22 (2007) 290–296. http://www.jstor.org/stable/44490536.
[61] E.F. Mutsamba, I. Nyagumbo, W. Mupangwa, Forage and maize yields in mixed crop-livestock farming systems: enhancing forage and maize yields in mixed crop-livestock systems under conservation agriculture in sub-humid Zimbabwe, NJAS - Wageningen J. Life Sci. (2019) 1–10, https://doi.org/10.1016/j.njas.2019.100317.
[62] V. Makuvaro, S. Walker, A. Munodawafa, T.P. Masere, C. Murewi, I. Chagonda, An overview of current agronomic practices of smallholder farmers in semi-arid Central and Western Zimbabwe, Afr. J. Agric. Res. 9 (2014) 2710–2720, https://doi.org/10.5897/ajar11.606.
[63] B. Sims, J. Kenzle, Farm Power and Mechnization for Small Farms in Sub-saharan Africa, 2006 file:///y:/10853.pdf.
[64] D. Ampratwum, A. Dorvlo, L. Opara, Usage of tractors and field machinery in Oman, Agric. Eng. Int. CIGR J. Sci. Res. Dev. 6 (2004) 1–9.
[65] N. Mlengera, N. Wanjala, W. Tegambwage, T. Kakema, J. Kayeke, A. Ndunguru, Promotion of labour saving rice mechanization technologies in rain-fed low land and irrigated ecologies of Tanzania and Kenya, J. Nat. Sci. Res. 5 (2015) 52–59. https://core.ac.uk/download/pdf/234656145.pdf.
[66] T. Shonhe, The politics of mechanisation in Zimbabwe : tractors , accumulation and agrarian change, J. Peasant Stud. 49 (2022) 179–199, https://doi.org/10.1080/03066150.2021.1918114.
[67] X. Diao, J. Silver, H. Takeshima, J. Silver, Agricultural Mechanization and Agricultural Transformation, 2016. https://www.jica.go.jp/jica-ri/publication/booksandreports/l75nbg0000004aet-att/l75nbg0000004aik.pdf.
[68] F. Baudron, B. Sims, S. Justice, D.G. Kahan, R. Rose, S. Mkomwa, P. Kaumbutho, J. Sariah, R. Nazare, G. Moges, B. Gérard, Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheel tractors, conservation agriculture, and private sector involvement, Food Secur. 7 (2015) 889–904, https://doi.org/10.1007/s12571-015-0476-3.
[69] K.O. Yoro, M.O. Daramola, CO2 emission sources, greenhouse gases, and the global warming effect, in: M.R. Rahimpour, M. Farsi, M.A.B.T.-A, C.C. Makarem (Eds.), Adv. Carbon Capture Methods, Technol. Appl., Woodhead Publishing, 2020, pp. 3–28, https://doi.org/10.1016/B978-0-12-819657-1.00001-3.
[70] R. Lal, Reducing carbon footprints of agriculture and food systems, Carbon Footprints 1 (2022) 3, https://doi.org/10.20517/cf.2021.05.
[71] E. Aguilera, G.I. Guzmán, M. González de Molina, D. Soto, J. Infante-Amate, From animals to machines. The impact of mechanization on the carbon footprint of traction in Spanish agriculture: 1900–2014, J. Clean. Prod. 221 (2019) 295–305, https://doi.org/10.1016/j.jclepro.2019.02.247.
[72] P. Spugnoli, R. Dainelli, Environmental comparison of draught animal and tractor power, Sustain. Sci. 8 (2012), https://doi.org/10.1007/s11625-012-0171-7.
[73] J. Liu, C. Xia, D. Jiang, G. Shang, J. Han, Y. Sun, Determination and application of maximum efficiency curve of crawler electric tractor motors, Math. Probl Eng. 2021 (2021), https://doi.org/10.1155/2021/1310926.
[74] A. Das, Y. Jain, M.R.B. Agrewale, Y.K. Bhateshvar, K. Vora, Design of a concept electric mini tractor, in: 2019 IEEE Transp. Electrif. Conf. ITEC-India, 2019, 2019, pp. 10–14, https://doi.org/10.1109/ITEC-India48457.2019.ITECIndia2019-134.
[75] LFSP, Sorghum Prodution Training Manual, 2017. https://lfspzwcom.files.wordpress.com/2017/05/sorghum-production-training-manual-final-with-page-number.pdf.
[76] R.K. Jat, R.G. Singh, R.K. Gupta, G. Gill, B.S. Chauhan, V. Pooniya, Tillage, crop establishment, residue management and herbicide applications for effective weed control in direct seeded rice of eastern Indo–Gangetic Plains of South Asia, Crop Protect. 123 (2019) 12–20, https://doi.org/10.1016/j.cropro.2019.05.007.
[77] J. Herbek, L. Murdock, Planting and Drill Calibration, (n.d.) 20–24.
[78] A. Oswald, J.K. Ransom, J. Kroschel, J. Sauerborn, Transplanting maize and sorghum reduces Striga hermonthica damage, Weed Sci. 49 (2001) 346–353, https://doi.org/10.1614/0043-1745(2001)049[0346:tmasrs]2.0.co;2.
[79] E.M. Young, M.S.A. Mattram, Transplanting sorghum and millet as a means of increasing food security in semi-arid low-income countries. http://www.fao.org/docs/eims/upload/agrotech/1901/r7341Pt1.pdf, 2003.
[80] P.K. Guru, N. Chhuneja, A. Dixit, P. Tiwari, A. Kumar, Mechanical transplanting of rice in India: status, technological gaps and future thrust, ORYZA- An Int. J. Rice 55 (2018) 100, https://doi.org/10.5958/2249-5266.2018.00012.7.
[81] H. Tibugari, C. Chiduza, A.B. Mashingaidze, A survey of problem weeds of sorghum and their management in two sorghum-producing districts of Zimbabwe, Cogent Soc. Sci. 6 (2020), https://doi.org/10.1080/23311886.2020.1738840.
[82] V. Hatti, B.K. Ramachandrappa, Mudalagiriyappa, Weed dynamics in conservation agricultural systems as influenced by conservation tillage and nutrient management practices under rainfed finger millet, Indian J. Weed Sci. 50 (2018) 355, https://doi.org/10.5958/0974-8164.2018.00076.x.
[83] T. Muoni, L. Rusinamhodzi, C. Thierfelder, Weed control in conservation agriculture systems of Zimbabwe: identifying economical best strategies, Crop Protect. 53 (2013) 23–28, https://doi.org/10.1016/j.cropro.2013.06.002.
[84] R. Mandumbu, P. Jowah, C. Karavina, H. Tibugari, Integrated weed management in Zimbabwe's smallholder sector, where are we?: a review, Mod. Appl. Sci. 5 (2011) 111–117, https://doi.org/10.5539/mas.v5n5p111.
[85] L.A. Derscheid, H. DeLong, Weed Control Equipment, 1956. http://openprairie.sdstate.edu/agexperimentsta_circ/122%0A.
[86] J. Van Loon, L. Woltering, T.J. Krupnik, F. Baudron, M. Boa, B. Govaerts, Scaling agricultural mechanization services in smallholder farming systems: case studies from sub-Saharan Africa, South Asia, and Latin America, Agric. Syst. 180 (2020) 1–13, https://doi.org/10.1016/j.agsy.2020.102792.
[87] G. Kyser, J. Roncoroni, R. Wilson, Chemical Application Methods for Herbaceous Weeds, n.d. https://ucanr.edu/sites/csnce/files/57613.pdf.
[88] K.C. Harrington, H. Ghanizadeh, Herbicide application using wiper applicators - a review, Crop Protect. 102 (2017) 56–62, https://doi.org/10.1016/j.cropro.2017.08.009.
[89] G.A.Z. Abdulai, Between-row Mower Design for Weed Control in Organically Grown No-Till Soybeans, University of, Missouri, 2018. MSc Thesis, https://mospace.umsystem.edu/xmlui/bitstream/handle/10355/66311/research.pdf?sequence=1&isAllowed=y.
[90] M. Abu-Dieyeh, A. Watson, Impact of mowing and weed control on broadleaf weed population dynamics in turf, J. Plant Interact. 1 (2005) 239–252, https://doi.org/10.1080/17429140601015226.
[91] A. Bolat, U. Sevilmis, A. Bayat, Flaming and burning as thermal weed control methods: a review, eurasian, J. Agric. Res. 1 (2017) 52–63. https://dergipark.org.tr/tr/download/article-file/485355.
[92] S. V Stepanovic, Positioning an Innovative Flame-Weeding Technology into Crop Production: MSc Thesis, University of Nebraska - Lincoln, 2013. https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1073&context=agronhortdiss.
[93] M.D. Nikam, S.H. Thakare, V.P. Khambalkar, S.S. Karhale, Study of economics of manual and mechanical harvesting method of sorghum crop, Int. J. Curr. Microbiol. Appl. Sci. 6 (2017) 1211–1217, https://doi.org/10.20546/ijcmas.2017.606.140.
[94] IDRC, Report on Addressing Post-Harvest Constraints of Small Millets in South Asia Part of Revalorizing Small Millets in the Rainfed Regions of South Asia, 2014.
[95] H.D. Upadhyaya, V.G. Reddy, D. Sastry, Regeneration guidelines: finger millet (2008) 1–7.
[96] SHRACHI, spr-1200-paddy-reaper, (n.d.). http://5.imimg.com/data5/GX/XI/MY-2218129/spr-1200-paddy-reaper.pdf.
[97] DAFF, Pearl Millet —Production Guideline, 2011.
[98] G. Armah-Agyeman, J. Loiland, R. Karow, W.A. Payne, C. Trostle, B. Bean, Grain Sorghum, 2002. https://catalog.extension.oregonstate.edu/em8794.
[99] FAO, Sorghum, Post-Harvest Operations, 1999.
[100] K. Abdulkarim, K. Abdulrahman, I. Ahmed, S. Abdulkareem, J. Adebisi, D. Harmanto, Design of mini combined harvester, J. Prod. Eng. 20 (2017) 55–62, https://doi.org/10.24867/jpe-2017-01-055.
[101] T. Shonhe, Tractors and agrarian transformation in Zimbabwe: insights from Mvurwi. https://opendocs.ids.ac.uk/opendocs/handle/20.500.12413/14399, 2019.