ABSTRACT

The low level of engineering technology inputs into agriculture is a major constraint hindering the modernization of agriculture and food production in many parts of Africa. Cassava (Manihot esculenta Crantz), is a climate resilient crop grown by smallholder farmers in most sub-Saharan Africa countries. Cassava provides dietary carbohydrates for over 800 million people globally. It is also a bio-fuel source that can replace fossil fuels. Africa is not visible in the cassava industrialisation and export market because it depends on over-aged farmers, who use manual tools and traditional production methods that do not attract the youth. One major challenge to all year-round cassava production for industry and export in Africa is the time consuming, labour intensive and expensive manual harvesting method. Manual cassava harvesting is full of drudgery and takes 5 to 10 minutes to uproot a plant, depending on soil condition. The main objective of this paper is to demonstrate and popularise an innovative mechanical cassava harvester developed in Ghana (OAPI patent No. 17219), to mechanise and modernise cassava production in Africa. The device harvests at a rate of one plant per second or less especially when the ground is hard. For the innovation to be disseminated successfully, tractor operators and smallholder farmers must be trained to acquire mechanised production methods. Cassava farmers need to change from planting in the traditional haphazard manner to adopt row and ridge planting to comply with mechanical harvesting at plant maturity. The device is to up-scale and increase cassava production for food security, industrial use and export in Africa.

Keywords: Cassava, mechanical harvester, drudgery, aging farmers.

INTRODUCTION

Cassava (Manihot esculenta Crantz) is an important food security crop in the tropical and sub-tropical areas of the world, with its roots providing dietary carbohydrates for over 800 million people (FAO, 2013). Global cassava production for 2016 was estimated at 288.4 million tonnes, with 54% 157.2 (million tonnes) by Africa, 32% by Asia, and 14% produced in South America (FAO, 2016). Unlike Africa, Asia encourages the development of cassava crops for industrial and energy purposes (UNCTAD, 2013). In China, cassava has been listed as one of the main raw materials that can be used for ethanol production and animal feed in future (Chengyu et al., 2010, Zhiguo et al, 2008, DFAO, 2016). In Africa, cassava is the second most important food staple after maize in terms of calories consumed (FAOSTAT, 2012). Today the four leading cassava producing countries in Africa are Nigeria, Democratic Republic of Congo, Ghana and Angola (FAO. 2012, Nweke, 2004). In southern...
Cassava production in Africa is mainly by smallholder farmers, who depend on manual tools for their field operations. However, a lot of challenges such as small farm holdings that are fragmented and dispersed prevent the development and use of modern equipment for its production (Kolawole et al., 2010). The most difficult and time-consuming operation in cassava production is cassava harvesting (Yulan, et al., 2012, Agbetoye 2005, Nweke et al., 2002). Cassava is mostly harvested manually by lifting the lower part of the stem and pulling the roots out of the ground, then removing the tubers from the base of the plant by hand. The upper parts of the stems with the leaves are removed before harvest. Manual harvesting tools such as levers, cutlasses, hoes, mattocks and ropes can be used to assist in uprooting the tubers. The appropriate manual harvesting method under the current practice depends on soil texture and moisture regimes (Adjei-Nsiah, S., 2012, Peipp and Maehnert. 1992). Harvesting cassava roots by hand is easy if the soils are sandy or during the rainy season. In heavier soils or during the dry season, harvesting usually requires digging around the roots to free them and lifting the plant. To facilitate lifting, the plant is usually coppiced to about 30 to 50 cm above ground. The protruding stem is used to lift the roots out of the ground. While lifting, care should be taken not to break the roots, as this will lead to losses if broken roots are not retrieved from the soil and to contamination that may accelerate spoilage. Manual harvesting of cassava consumes a lot of energy and time and the operation is not mechanised in most countries in Africa (Amponsah et al., 2014; Bobobee et al., 2013; Agbetoye and Ileybare, 2012; Agbetoye, 2005). However, if large-scale tuber production and harvesting is envisaged, development of a mechanical harvesting device is desirable. According to Agbetoye and Ileybare, (2012), several researchers are working extensively in an attempt to come up with effective manual, semi-mechanized/mechanized methods of harvesting cassava. After clearing the land, harvesting is the most labour-intensive operation, and agricultural engineers have sought to mechanise it. Mechanical harvesting of cassava is difficult because of the non-uniform geometry of the roots in the ground. Methods of mechanical cassava harvesting have some advantages, such as high efficiency, low tuber damage and low cost (Xue et al., 2010 and Wang et al., 2011). Nevertheless, a few cassava harvesters have been designed and some are in operation, mostly by large-scale farmers in Asia and Latin America (FAO, 2013.). Cassava roots can be harvested at any time of the year. Some farmers harvest as early as six months after planting while others may leave the crop for 18 to 24 months after planting (MAP). The food quality of roots, particularly the starch content, increases with time up to an optimal period of 12 to 15 MAP, after which there is a loss of quality, mainly due to increased ligneification (IFAD/FAO, 2004, Aye, 2012). Planting of cassava is traditionally done on the flat in a random manner, but recently, Bobobee et al., (2013) are recommending planting cassava in rows and preferably on ridges to aid mechanical weeding and harvesting to support industrial use of the crop. According to Philippine Root Crops Information Service (2005), harvesting cassava during relatively dry soil is the best since the soil does not stick to the harvesting implement or roots easily. This is the time when manual harvesting is also very difficult. During the harvesting process, the cuttings for the next crop are selected and kept in a protected location to prevent desiccation.
Today with the interest to use cassava for various industrial products such as high-quality cassava flour, starch, and other alcoholic beverages, large-scale cassava production is attracting attention on the African continent, especially in Nigeria and Ghana (FAO, 2016). It makes economic and environmental sense to produce more cassava not only for food in the future as climate change, population growth, energy and water supplies add pressure to worldwide food systems. However, cassava harvesting for large-scale industrial processing is a major constraint and presently, there is no known commercial mechanical cassava harvesters in use by many cassava producers on the continent. The present situation especially to harvest all year round demands technological interventions by agricultural engineers and technologists to make cassava an industrial commercial crop on a sustainable basis. To address the above challenges, agricultural engineers at the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana collaborated with their counterparts from the University of Leipzig in Germany developed an appropriate mechanical cassava harvesting technology, (The TEK MCH) to harvest cassava root tubers by the ‘dig and expose’ principle.

1.1 Objective

The main objective of this paper was to identify challenges, opportunities and prospects for cassava production in Africa through the introduction, demonstration and promotion of a novel mechanical cassava harvesting technology in sub-Saharan Africa. The specific objectives were to;

- Evaluate the TEK Mechanical Cassava harvester, an innovative device to harvest cassava mechanically,
- Establish mechanised cassava pilot farms on ridges and flat land to test mechanical cassava harvesting in different agro-ecological zones in Ghana and South Africa,
- Evaluate the draught and other implement performance parameters in mechanical cassava production and harvesting,

Compare mechanical cassava harvesting techniques with manual harvesting methods in terms of field capacity, root damage and drudgery.

2.0 MATERIALS AND METHODS

2.1 Project Sites (Ghana)

Pilot study sites at Anwomaso and Akatsi in Ghana were selected to demonstrate mechanical cassava production and harvesting. The locations were selected based on their potential for higher cassava production levels on commercial basis. In Ghana, Anwomaso (KNUST) arable farms (6°41’56.75"N, 1°31’25.85"W) and 274m above sea level (a.s.l), is in the tropical rain forest zone. Anwomaso experiences bi-modal tropical rainfall pattern and wet semi-equatorial climate. It is characterized by double maxima rainfall lasting from March to July and again from September to November. The mean annual rainfall is 1200 mm, which is ideal for minor season cropping. Temperatures range between 20°C in August and 32°C in March. Relative humidity is fairly moderate but quite high during rainy seasons and early mornings. Soils in Anwomaso are mainly Forest Acrisols (FAO/UNESCO, 1998). The climate in Akatsi is characterized by high temperatures (21° C-34.5° C), high relative humidity (85%) and moderate to low rainfall regime (1,084 mm) with distinct wet and dry seasons of about equal lengths. Akatsi has Savanna Cambisols (FAO/UNESCO, 1998) soil types characterized as moderate to well-drained, deep red to brown loamy sand to sandy loam topsoil over coarse sandy loam to clay loam sub-soils.

2.2 Project Sites in South Africa

Two project sites were selected in Limpopo and Mpumalanga provinces of South Africa. The Limpopo field was located at the University of Venda Experimental farm, Thohoyandou in the sub-tropical Vhembe district (22° 58’ 57” S, 30° 26’ 25” E), at an elevation of 595 m asl. The climate at Thohoyandou is characterized by moderate temperatures (15° C- 24.5° C), high relative humidity (52.3 -81.1%) and moderate to high rainfall regime (1069.3 mm). The
Limpopo field has *Shordlands* soil form with high clay content and classified as Nitisols (FAO/UNESCO, 1998). The Nelspruit site (25° 27’ 21” S, 30° 59’ 49” E) in Mpumalanga is characterised by deep, well-drained loamy sand soils of the *Glenrosa* series and classified as Cambisols (FAO/UNESCO, 1998). The Nelspruit site is located on the Agricultural Research Council’s Institute for Tropical and Sub-tropical Crops (ARC-ITSC) orchards. Both areas (Univen and Nelspruit) are dominated by a Savannah biome with vegetation type of sour lowveld bushveld.

### 2.3 Seedbed preparation field layout and crop establishment

The fields (one ha minimum) at all sites were ploughed with disc ploughs in Ghana and mouldboard ploughs in South Africa. All fields were deep ploughed to be free from hidden obstructions and harrowed with disc harrows to produce smaller clod sizes, before ridging. Both the Ghanaian and the South African fields were ridge landforms according to Bobobee et al., (2013). Ridges were constructed with an average height of 0.3m and spaced 1.2m apart (crest to crest) to accommodate the tractor track width. Intra-row spacing was varied for optimum plant population density of 10,000 plants/ha. Cassava stakes were cut into 20–25 cm length with 8–10 nodes and planted at an inclined angle of about 30–60° with half of the length buried in the soil.

### 2.4 Soil mechanical analysis

Soils were sampled at random locations at the corners and mid-sections of the fields to measure soil penetration resistance, bulk density and moisture contents in the 0-40 cm layer at 10 cm intervals. Composite samples were taken at depths of 0-20, 20-40 and 40-60cm using the soil auger for soil physico-chemical analysis and particle–size distribution and texture (USDA textural triangle). These soils were chemically analysed to test for their pH-levels (1:1H₂O), Organic Carbon content (%), total Nitrogen (%), Exchangeable cations in me/100g (Ca, K, Mg and Na), Base sat (%), T.E.M, C.E.C (me/100g), Exchangeable A (Al + H) and Available Brays (ppmP and ppmK).

### 2.5 Crop care and farm sanitation

All the fields planted were on long fallow lands and no organic or inorganic fertilisers were applied to the cassava in both countries. In addition to the pre-emergence chemical weed control in the Ghanaian fields, weeding was mainly by manual methods using hoe and machete every two–three months after planting (MAP) depending on weed infestation levels. Farm boundaries and access roads were occasionally sprayed with herbicides. Fields were maintained clean close to harvesting time to minimise residues clogging the harvester.

### 2.6 The mechanical harvester

The fully-mounted mechanical cassava harvester with a slatted conical mouldboard without any transport system (Fig 1) was adapted from a Leipzig model and developed to operate on the “dig and expose” principle.

![Figure 1: Cassava harvester according to the “dig and pull principle” being commissioned in South Africa](image)

The harvester mass is 300 kg, and it requires 47-60 kW pusher-type motive power. The cutting width is 1000 mm with a depth of cut of 240-400 mm. At a working speed of 2.1-6.7km/h and depending on soil condition, operator experience and skill, the implement can harvest 0.5 – 0.7 ha/h at a fuel consumption of 15-23 l/ha. The detailed description and performance has been discussed by Bobobee et al., (2013) and Amponsah et al., (2014).

### 2.7 Draught, speed and slip measurements
In Ghana the draughts developed by the ploughs, harrows and harvester as they operate to prepare seedbed and excavate the cassava root cluster were measured using a 10 tonne commercial electronic dynamometer (RON 2125S®, Israel) with a digital data logger (Fig. 2). In operation, the dynamometer was attached between a pulling tractor and the instrumented tractor that hitches the implement. Draught forces were measured for the implements in the transport position (no load) and when engaged in the soil during work and harvesting (load). Load conditions and draught force measurements were taken after the implement has stabilized in the soil at the operating depth. Average speed of operation was derived from the time taken for the tractor implement assembly to traverse a fixed distance marked on the field. To measure implement slip, the distance covered by 10 rear tyre revolutions when working and in no-load positions were used. Figure 2 shows the implement draught measurement procedure with one tractor pulling the instrumented one hitching a harvester. The RON 2125S dynamometer logs the force measurements, which were later transferred to a computer and analysed with popular spreadsheet programmes.

In South Africa, the three-point hitch dynamometer and data logging instrumentation (Figure 3) developed by the ARC-IAE was used to determine, speed, fuel consumption, slip drawbar force, and engine power required by the implements tested. The dynamometer measures forces on every hitch point i.e. vertically, horizontally as well as laterally. The resultant pulling force is measured by using the data from all three measuring points. The correct setting of the 3-point hitch dynamometer is important to be able to sense the forces and other parameters generated by the implement and the tractor. Calibration of all the bridge channels on the data logger was performed by lowering the implement to a stable position on the ground. The data logging process and the test runs were performed at the same constant working speed and depth. During the test run all the instrumented data were logged at 100 Hz onto the data logger memory bank. After operating the implements, the disturbed soils created by the implements were excavated to expose the width and depth of work and to measure the profile created. The data was then downloaded to the computer on the base station using popular spreadsheet programmes to process and to generate reports for each implement.

Figure 2: Implement draft determination by RON 2125S electronic dynamometer

2.8 Soil Profile measurement

The profile of the soil disturbed soil by each implement was measured using laser measuring units on a steady beam to profile both the horizontal width of cut and the vertical depth of the cut soil (Figure 4). The profiled area is then calculated.

Figure 3: Three-point hitch dynamometer

Figure 4: Soil profile measurement using the laser beam technology
2.9. Heart rate and drudgery estimation

In this study, heart rate is used as proxy for the intensity of physical activity or manual work in agriculture. Heart beats of manual workers and tractor operators were measured at rest before work, during work and after work (recovery). This is to estimate the energy expenditure and stress or drudgery induced in cassava production. In Fig. 5, heart rate data were collected simultaneously at a sampling rate of 5s interval using the POLAR® RS800CX Accurex instrumentation (Polar Electro, Oy, Finland). The mounting, installation and performance of the heart rate sensor and monitor is described in greater detail, by Bobobee and Girma (2007). Data from the receiver is downloaded to a computer for visualisation and processing by popular spreadsheets. Drudgery was estimated for manual planting, weeding and harvesting and mechanical land preparation and harvesting activities of operators by evaluating the heart beats of the workers during work. In this paper, only harvesting drudgery has been reported. Corresponding energy consumption values were used to calculate the mandatory rest periods required for each operation.

\[ T_r = 60 \times \left(1 - \frac{250 or 300}{P}\right) \text{min/h} \quad (1) \]

Where, 

- \(T_r\) = Total rest period (min/h)
- \(P\) = Gross energy consumption (Watts)

250 W is used as numerator in the hot tropics of sub-Saharan Africa, while 300 W is used for the cool temperate and sub-tropical areas of South Africa.

Using the average working heart rates obtained for a particular field activity the corresponding gross energy consumption (Watts) was determined and used to compute the mandatory rest period required to enable the duration a worker can recuperate and gain lost energy. The more intense the physical activity as in the manual harvesting (Figure 6), the higher the heartbeat of the worker with a corresponding higher gross energy consumption leading to a longer rest period. Mechanical harvesting (Figure 7) on the other hand is less strenuous and does not demand longer rest periods.
2.10 Root tuber damage assessment

Cassava deteriorates from 24 h after harvesting due to its high moisture content. Any bruises and damage will accelerate tuber deterioration and spoilage (Bayoumi et al., 2008). Cassava root damage caused during harvesting was due to either shallow harvesting depths or relatively deeper root penetration or longer horizontal root spread beyond the harvester operating width. Quantitative methods were employed to determine root damage. Damaged and whole tubers after harvesting were separated and weighed (Figure 8). The percentage damage for each harvesting method was computed by dividing the damaged cassava weight by the total yield. Farmers, market women and processors use the qualitative (eye-ball ing) approach to assess damage. From farmers and processors perspectives, cassava root damage was assessed when the tubers do not come out whole after harvesting but with cuts and bruises that could render it unsuitable for long storage.

Figure 8: Cassava root tuber damage assessment in the field

3.0 RESULTS AND DISCUSSION

3.1 Soil physico-chemical properties

Table 1 shows the soil chemical and mechanical properties at land preparation at all sites and at harvest at the Ghana sites Anwomaso soils were strongly acidic up to 60 cm depth. With such acidity levels, important soil nutrients such as Potassium and Phosphorus will not be easily available for plant growth (Brady and Weil, 1996). Akatsi soils on the other hand, had moderate acidity after ploughing and at harvest. With the relatively high yield obtained from the project sites 15 MAP, it means that cassava can be cultivated in soils with pH ranging from 4.4 – 6.0 without adverse yield loss, which agrees with the findings of O’Hair, (1995), Philippine Root Crops Information Service, (2005) and Okigbo, (2007) that cassava can survive in poor soils with pH ranging from 4 to 9. Even though the pH appeared to be unsuitable for crop growth, the cassava yield was not seriously affected at the Ghana locations.

Soil organic carbon was generally low (<2%) at the Ghana sites but were slightly better at Anwomaso within the topsoil (0-20 cm), with Akatsi having extremely low organic carbon (%) at ploughing and at harvest. Low C.E.C (5 - 15 me/100g) and very low (<5 me/100g) indicate low to moderate soil fertility, respectively. All the study sites generally fell within the range of moderate soil fertility and thus were suitable for plant growth after ploughing. At harvest however, the soil fertility was lower for the sites indicating that, the soil fertility had been used and this reflected in the high cassava crop yield at both places. Nitrogen contents were low to medium at planting, and very low (<0.1) for all sites at harvest. This indicated the cassava crops utilized the soil Nitrogen for their growth and development as expected. Soils at Anwomaso are predominantly sandy loam at 0-20cm and sandy clay to sandy clay loam at 20-60cm soil depth. Soils at Akatsi are mainly loamy sand from 0-60 cm soil depth. Soils at the Anwomaso had better nutrient and water holding capacity compared to that at Akatsi.

In South Africa, soil organic carbon was generally higher (<3%) at the Venda site but lower (<1%) at Nelspruit sites within all horizons (0-60 cm). Low C.E.C (1.9 - 18 me/100g) and very low (<5 me/100g) indicate low to moderate soil fertility, at the Venda and Nelspruit sites, respectively. All the study sites in Ghana and South Africa generally fell within the range of moderate soil fertility and thus were suitable for cassava growth after ploughing.
| Location (Soil depth) | pH (1:1 H₂O) | O.C. (%) | C.E.C (me/100g) | N (%) | Sand % | Silt % | Clay % | Soil Texture | FAO (UNESCO) Classification (1998) |
|----------------------|-------------|---------|-----------------|-------|--------|-------|-------|--------------|---------------------------------|
|                      | AP         | A       | AP               | AH    | AP     | AH    | AP    | A            |                                 |
| Akatsi               |             |         |                  |       |        |       |       |              |                                 |
| 0-20cm               | 5.70       | 6.12    | 0.22             | 0.34  | 2.45   | 5.16  | 0.16  | 0.03         | 83.02                           |
| 20-40cm              | 6.00       | 6.12    | 0.18             | 0.27  | 1.60   | 4.43  | 0.13  | 0.02         | 81.70                           |
| 40-60cm              | 5.60       | 5.91    | 0.15             | 0.17  | 1.94   | 4.17  | 0.11  | 0.02         | 80.46                           |
| Anwomaso             |             |         |                  |       |        |       |       |              |                                 |
| 0-20cm               | 5.50       | 4.83    | 0.96             | 0.87  | 3.64   | 6.61  | 0.23  | 0.11         | 64.94                           |
| 20-40cm              | 5.00       | 4.78    | 0.52             | 0.47  | 3.72   | 7.02  | 0.13  | 0.05         | 50.70                           |
| 40-60cm              | 5.00       | 4.60    | 0.43             | 0.23  | 3.53   | 6.87  | 0.10  | 0.02         | 43.10                           |
| Venda                |             |         |                  |       |        |       |       |              |                                 |
| 0-20cm               | 5.83       | na      | 2.70             | na    | na     | na    | na    | 22           | 58                              |
| 20-40cm              | 5.56       | 1.53    | 13.87            | 1.92  | 13.581 | 4.824 | 22    | 11           | 10                             |
| 40-60cm              | 5.29       | na      | na               | 0.69  | na     | na    | 0.69  | 0.69         | 0.69                           |
| Nelspruit            |             |         |                  |       |        |       |       |              |                                 |
| 0-20cm               | 6.42       | na      | 0.69             | na    | 2.328  | na    | na    | 80           | loamy sand                      |
| 20-40cm              | 6.42       | 0.69    | 1.799            | 0.74  | 4.824  | 0.74  | 80    | 80           | loamy sand                      |
| 40-60cm              | 6.08       | 0.74    | 4.824            | 0.74  | 4.824  | 0.74  | 80    | 80           | loamy sand                      |

Table 1: The soil chemical analysis results (pH, O.C., C.E.C., N and Soil Texture) at Akatsi, Anwomaso and Venda and Nelspruit during ploughing (AP) and at harvest (AH) [na = not available at reporting time]
3.2 Soil mechanical properties

The soil bulk densities, cone index and moisture contents at the Ghana sites before ploughing and at harvest are shown in Fig 9. There is a general increase in bulk density with depth for all sites before ploughing and at harvest. At harvest soil bulk density ranged from 1.56 – 1.68 g/cm$^3$ at Anwomaso, 1.45 – 1.57 g/cm$^3$ and 1.54 – 1.65 g/cm$^3$ at Akatsi with increasing soil depth. This trend agrees with the findings of Arshad et al., (1996), that bulk density increases with depth in the soil profile.

The soil bulk densities for Anwomaso site was lower at ploughing and harvest than for Akatsi. The high bulk density at ploughing at Akatsi could be attributed to the fact that the soils were more consolidated causing the clods to easily compact. The high bulk densities at harvest still made harvesting possible for the TEK mechanical cassava harvesters. Report by USDA, (1999) considered that compacted soil layers have high bulk densities. Bobobee et al, (1994) reported a maximum soil bulk density of 1.82 g/cm$^3$ at harvest for the Leipzig harvester. Soil core sizes range from 15 cm diameter by 15 cm high to rectangular cores 1 cm thick and 5 cm across. Soil bulk density as an important factor influences soil microscopic properties like large pores, hydraulic conductivity, penetration resistance, etc, which are significant in land utilisation (Koolen 1987, Gupta et al, 1989).

The mean soil penetration resistances before ploughing (BP) and at harvest (AH) for Anwomaso, and Akatsi sites increased with depth (Fig.9). Penetration resistance is one soil physical property modified by tillage. In this project, the mechanical resistance of the soil to a penetrometer is related in a poorly understood manner to clay mineralogy and to soil physical properties such as dry bulk density ($D_b$), texture, structure, water content and percent organic matter, Cassel (1982). Tillage operations (ploughing, harrowing and harvesting), alter penetration resistance primarily by effecting changes in $D_b$, structure, and water content. Bernier et al (1989), studied the soil disturbance of a winged sub-soiler in a sandy loam and clay soil. The bulk density profiles indicated that passage of the sub-soiler compacted the top soil while loosening the subsoil. They concluded that the effects of tillage on soil physical properties could not be satisfactorily interpreted by conventional statistics. At harvest, penetration resistance ranged from 1.77 – 2.24 MPa at Anwomaso, 0.73 – 1.53 MPa and 0.92 – 3.03 MPa at Akatsi with increasing soil depth. From fig. 9, it is clear that soil penetration resistance increased with increasing bulk density. Ploughing generally reduced the penetration resistance which agrees with the findings of Reichert et al., (2004).

From fig. 9, mean soil moisture content before ploughing and at harvest for Anwomaso, and Akatsi increased with increasing depth with the Akatsi soil being the driest. For the range of soil depth tested, soil moisture increased with depth and ranged from 12.06 – 15.69 % (d.b.) at Anwomaso and 1.02 – 3.71 % (d.b.) at Akatsi. The increasing moisture content down the soil profile could be due to the fact that the topsoil experienced more evaporation than lower horizons. The soil moisture content for Akatsi before ploughing decreased with increasing soil depth. This change could be attributed to the fact that it had rained the day before ploughing when the samples were taken and moisture had not infiltrated completely into lower horizons.
Figure 9: Graph of Mean Bulk Density (g/cm$^3$), Cone Index (kPa) and Moisture content (%) before ploughing (BP) and at harvest (AH) versus soil depth for the two Ghana trial sites.

3.3 Depth of tuber penetration and harvester performance

Figure 10 shows the mean root tuber depth of penetration when harvesting elite cassava varieties by both manual and mechanical means at 15 MAP for Akatsi and Anwomaso. From the graph, mechanical cassava harvesting on the ridge at Anwomaso had higher mean root tuber penetration depth of 26.01 cm compared with a mean root penetration depth of 24.96 cm at Akatsi.

Figure 10: Mean Depth of Cassava root tuber excavation (cm) for both ridge and flat landforms at Anwomaso and Akatsi at 15 MAP.
There was no significant difference (p<0.05) for the mean depth of root excavation for manual and mechanical harvesting at Akatsi, and Anwomaso. Mechanical harvester performance was evaluated under working depth, percentage root tuber damage, field capacity, fuel consumption, working speed, percentage wheel slip, draught force and tractor power requirement and energy consumption. The mean depth of mechanical harvester penetration at Anwomaso and Akatsi ranged from 24.00 - 27.00 cm. From fig. 10, the mean depth of harvester penetration at Anwomaso was higher than at Akatsi implying eminent higher root damage during harvest at Akatsi. To minimise damage, the harvester has to go deeper beyond the depth of root penetration. Odigboh and Moreira, (2002) and Sam and Dapaah, (2009) reported that ridges are able to control cassava roots tubers to reasonable depths to allow for optimum mechanical harvesting. Another reason could be due to the ease with which ridges were easily pulverized. The harvester cutting edge goes deeper under ridges and shatters the soil better during harvesting than on the flat landform. This is in agreement with what Ennin et al., (2009), reported that planting cassava on ridges had the advantage of higher cassava root yield, better and easier field management and the potential for mechanization to further decrease drudgery and increases the scale of productivity of cassava compared to planting on the flat.

3.4 Tuber Damage Assessment

From Figure 11, the mean percentage tuber damage at Anwomaso and Akatsi ranged from 9.5-10.8 and11.8-16.25% for both manual and mechanical harvesting.

The lowest mean percentage harvesting root tuber damage was recorded for cassava varieties that developed bunchy tubers and on ridges, compared to higher tuber damage for varieties that developed laterally, did not cluster but spread both in the latitudinal and longitudinal directions along rows and on ridges. Bobobee et al., (1994) reported 10.7-22% average tuber damage for the Leipzig mechanical harvester while Kolawole et al., (2010) reported 23.3% tuber damage for another mechanical harvester. Generally, the higher percentage root tuber damage for Akatsi could be attributed to the low moisture content, high bulk density, high penetration resistance (fig 11) and the relatively low depth of harvester penetration (fig.10) at harvest.

3.5 Field capacity for mechanical harvesting

From Figure 12, mechanical harvesting ranged from 2.2 – 2.23 (h/ha) whilst manual cassava harvesting capacities ranged from 105 - 239 (h/ha), confirming a higher amplification of efforts with the mechanical harvester. Bobobee et al, (1994) reported a range of 2.63 – 4.0 h/ha for the Leipzig harvester. Ospino et al, (2007) also, reported a mean field capacity range of 1.0 – 1.6 h/ha for the CLAYUCA Cassava Harvester Model P600, whilst Oni (2005) reported a range of 0.83 – 1.25 h/ha for the NCAM harvester. The low moisture content at Akatsi (Fig.9) compared to Anwomaso, could be responsible for the difficulty to manually harvest both on the ridge and on the flat landforms. This confirms the fact that mechanical harvesting is most suitable during the dry season while manual harvesting on the other hand is preferred during the wet season as reported by Bobobee et al., 1994 and Ospino et al., 2007. Nweke et al., (2002) reported a labour requirement of 22-63 man-days per hectare for manual harvesting of cassava. Comparing the capacities obtained for mechanical and manual harvesting methods in Fig 10, it confirms that manual cassava harvesting is more time consuming and could be full of drudgery than mechanical harvesting. The high man-hours required to manually harvest at Akatsi strongly correlates with the low soil moisture content, high soil bulk density and penetration resistance and drudgery level, confirming that the harder the soil, the more difficult to harvest manually.
The results for the two sites show the above soils conditions do not adversely affect mechanical harvesting.

**Figure 11**: Cassava tuber damage (%) for the Ghana sites

**Figure 12**: Field capacity for manual and mechanical cassava harvesting for the Ghana sites
3.6 Fuel consumption, wheel slip and travel speed

Table 2 depicts the mean fuel consumption, wheel slip and travel speeds for mechanical cassava harvesting at Akatsi and Anwomaso. The harvester recorded the highest mean fuel consumption of 22.26 l/ha at Akatsi compared with 20.44 l/ha at Anwomaso. During the tests, it was observed harvesting on the flat has higher fuel consumption than harvesting on the ridges.

| Parameter                      | Akatsi  | Anwomaso |
|--------------------------------|---------|----------|
| Fuel consumption (l/ha)        | 22.26   | 20.44    |
| Wheel slip (%)                 | 12.92 – 14.93 | 8.19 – 14.80 |
| Travel speed (km/h)            | 4.98    | 5.49     |

Table 2 Mean tractor wheel-slip (%), fuel consumption and travel speed for mechanical cassava harvester at Akatsi and, Anwomaso

In Table 2 above, the mean harvesting tractor wheel-slip recorded for Akatsi and Anwomaso ranged from 12.92 – 14.93% are all within acceptable ranges for a deep soil engaging implement like the cassava harvester. Akatsi recorded the higher mean wheel-slip than Anwomaso. The sandy soils at Akatsi had the lowest moisture content and more likely to fail under the tires thus impeding soil grip and movement relative to the other sites.

The highest mean working speed of 5.49 km/h was obtained at Anwomaso, whilst the lowest speed of 4.98 occurred at Akatsi. However, no statistical difference (p<0.05) existed between the two sites. The above speeds are higher than the 2.4 – 4.1 km/h Bobobee et al., (1994) reported for the Leipzig mechanical harvester but lower than the values Ospino et al., (2007) reported for the CLAYUCA Cassava harvester prototype, which had an operational speed of 7.0 km/h. Several factors such as wheel slip, moisture content, depth of penetration, operator experience and skill etc. could have caused these differences in mean fuel consumption for mechanical harvest. The higher fuel consumption values at Akatsi could be due to the relatively dryer soil coupled with a higher soil bulk density and higher penetration resistance.

Figure 13, shows the typical profiles of the working speed, fuel consumption, engine and drawbar power for the harvester performance using the three-point hitch dynamometer and data logger instrumentation while working in South Africa. The values obtained fall within the acceptable limits as those recorded under Ghanaian conditions. The results are in agreement with Owen (1989), who investigated the effect of travel speed on draught forces and soil disturbances associated with sub-soiling and found that the draught force was significantly correlated with the square of travel speed.

3.7 Draught force and tractor power requirement

The draught force and other parameters of ploughs, harrows and harvester in Ghana and South Africa are summarised in Tables 3&4, respectively. Table 3, shows the mean draught force, average working speed, depth of harvester penetration, soil specific resistance (SSR), drawbar power and brake horse power (Brake Hp) observed for the harvester at the Ghana sites during harvest. The draught force values ranged between 9.214 kN to 14.52 kN for both sites. Taking drawbar power to Brake Horse Power (Brake Hp) ratio of 19% and knowing the width of cut for the harvester to be 1 metre, the SSR (kN/m²), Drawbar Power and Axle Power (Tractor Engine Power required) are calculated (Hunt, 1977).

In Table 4, the performance of the mouldboard plough, disc harrow and the harvester using the three-point hitch dynamometer and data logger in South Africa are shown. The speed, specific fuel consumption, engine power, wheel slip and work rate results agree with those obtained in Ghana for the harvester. The specific fuel consumption for the disc harrow is nearly 50% lower than the mouldboard plough and harvester.
Figure 13: Combined travel speed, fuel consumption and power profiles when using the harvester to plough in South Africa

Table 3: Draught forces of harvester used to calculate the tractor engine power requirement at Anwomaso and Akatsi.

| Site    | Draught force (kN) | Travel speed (km/h) | Depth (m) | SSR (kN/m²) | Drawbar power (kW) | Engine power (kW) |
|---------|--------------------|---------------------|-----------|-------------|--------------------|-------------------|
| Anwomaso | 9.21-11.03        | 1.22-1.32           | 0.24-0.266 | 34.82-46.03 | 11.24-14.56        | 59.48-76.75       |
| Akatsi  | 13.2-14.52        | 1.11-1.22           | 0.24-0.3  | 48.4-54.10  | 16.10-16.12        | 84.76-84.83       |

Table 4 Plough, harrow and harvester performance in South Africa

| Parameter           | Mouldboard plough | Disc harrow | Harvester |
|---------------------|--------------------|-------------|-----------|
| Speed (km/h)        | 5.35               | 9.05        | 5.01      |
| Fuel rate (l/h)     | 21.94              | 20.85       | 18.49     |
| Specific fuel consumption (l/ha) | 22.92   | 13.00        | 20.56     |
| Work rate (ha/day)  | 9.56               | 16.29       | 9.01      |
| Engine power (kW)   | 57.96              | 53.39       | 43.42     |
| Drawbar power (kW)  | 26.02              | 20.32       | 26.75     |
| Wheelship (%)       | 9.1                | 11.62       | 16.12     |
| Implement efficiency (kN/m²) | 31.59 | 91.72        |           |
| Area (m²)           | 0.58               |             | 0.22      |
| Working depth (mm)  | 250                | 140         | 200       |
| Width of cut (m)    | 1.8                | 3.3         | 1.0       |
| MC (%)              | 15                 | 15          | 15        |
| Clay (%)            | 12                 | 12          | 12        |
The area (depth and width) of cut of the three furrow mouldboard plough and the harvester after they work soil and the pulverized soil excavated has been profiled by the laser beam technology for measuring the depth and width of cut (figure 14). The profiles of the plough and the harvester confirmed the true depth and width of cut and the soil excavated. These parameters also affect the speed, slip, wheel slip and the drawbar force and power generated by the implements. As reported by Gill and Vandem Berg, (1975), quantitative evaluation of tillage implement performance requires a measurement of induced forces from the soil-tool interactions and a measure of soil conditions to determine when and how much change occurred in the soil. Forces applied to a tillage implements (plough, harrow and harvester) produce effects on the soil that were readily measured by the instrumentation used. In this study, tillage operations of the plough, harrow and harvester alter the soil that has been loosened, crushed, inverted, sheared, shattered etc. Several of these effects may occur simultaneously and logged by the instrumentation employed.

3.8 Drudgery Calibration

Figure 15 shows the profiles of the manual worker and tractor operator when engaged in cassava harvesting. The heart rate profiles for the manual harvesting were 60% higher than for mechanical harvesting. From the figure, the highest heart rate for the tractor operator corresponds to the average resting heart rate profiles for the tractor operator, confirming the higher drudgery levels in manual harvesting. Drudgery was calibrated using the harvesting energy consumption. The higher the heart rate, the higher the energy consumption and to protect the worker, there is need for longer rest periods to recuperate and gain lost energy.

![Area Profile](image)

**Figure 14**: Area (depth and width of cut) profiles for the 3-bottom mouldboard and mechanical harvester
3.9 Mean heart rate, gross energy consumption and mandatory rest period

Table 4 shows the mean heart rate (bpm), gross energy consumption (Watt) and total mandatory rest periods (mins/h) required by manual workers and tractor operators at Anwomaso, and Akatsi during cassava harvesting. Table 4 depicts a generally higher mean heart rate for manual cassava harvesting compared with mechanical harvesting at all sites.

Rest period for manual harvesting was observed to be low when soil moisture content was high and it was easy for manual harvesting compared with harvesting when the soil is dry. According to Ospino et al., (2007), in terms of energy expenditure manual harvesting was generally easier during the wet season compared to mechanical harvesting, because tractor experience higher wheel slip in softer soils. Knowledge of the total mandatory rest period required after every harvesting activity is important in order to determine the effective working hours for a field worker. For an eight (8) hour man-day, a tractor operator at Anwomaso would require a rest period of three (3) hours and twenty-one (21) minutes, making him to effectively work for only 4 hours and thirty-eight (38) minutes.

Table 5: Mean heart rate, gross energy consumption and rest period for manual workers and tractor operators at Anwomaso and Akatsi during cassava harvesting.

| Study site | Mean heart rate (bpm) | Energy Consumption (W) | Rest periods (min/h) |
|------------|-----------------------|------------------------|----------------------|
|            | Manual | Tractor operator | Manual | Tractor operator | Manual | Tractor operator |
| Akatsi     | 119.65 | 96.86         | 746.27 | 487.90         | 39.90  | 29.26           |
| Anwomaso   | 112.42 | 91.58         | 664.91 | 426.65         | 37.44  | 24.84           |
| Lsd        | Ns     | ns            | ns     | ns             | ns     | ns              |

Figure 15: Heart rate profiles to assess drudgery for manual workers and tractor operator
From Table 5, gross energy consumption is directly proportional to the total rest period required, confirming that the more the energy consumed during an activity, the more the rest period required to recuperate and to compensate for the lost energy.

CONCLUSIONS

The mechanical harvester was developed and evaluated in comparison with manual harvesting and found to have performed soil pulverization and tuber uprooting best during the peak of the dry season when the soil was dry and hard. After harvesting the field was left ploughed for subsequent harrow and planting, thus saving time, fuel and cost. The depth of penetration and width of cut of the harvester affected the draught, speed, slip, fuel consumption of the tractor, and the capacity of the tractor to pull it. The harvester did not affect the drudgery of the operator since the heart rate profile of the harvester was similar to the heart rate profile of a disc harrowing. The study revealed that several factors are critical for successful mechanised harvesting of fully matured cassava crop. These include ridging, tractor speed, wheel slip, soil moisture content, cone index, depth of penetration of digging share, depth and spread of root cluster as it affects damage to roots.

The cassava harvester developed a capacity of 2.2-2.3 h/ha, and it can harvest in two hours what 60-114 people can do in a day. The drudgery involved in manual and mechanical harvesting is evaluated using the average heart beats of workers and tractor operators to determine the energy consumption and the mandatory rest periods required. The heart rate profiles for manual harvesting were 80% higher than for mechanical harvesting. The ease of mechanical harvesting is explained by the low heart beat profiles, energy consumption and rest periods of the tractor operator compared to those of the manual harvester.

Soil water content depletion during the dry season prior to seedbed preparation and at harvest resulted in increased soil resistance to penetration. In addition, draught, power, wheel slip, and fuel consumption were increased. Draught developed by the harvester was equal to that recorded for the three-furrow mouldboard plough. Drawbar power required to pull this harvester at a depth of 25-30 cm and at a field forward travel speed of 1.11 - 1.32 m/s was a low 16-17 kW.

Fuel consumption of the harvester was equal to that of mouldboard ploughing and almost double that of harrowing. The high fuel consumption noticed with the harvester might be due to the high slip, which also depended on the low soil moisture content at the time of harvesting, the high soil penetration resistance, and the depth of penetration of the lifter, the width of cut and the area and weight of excavated soil.

Root damage of 11-17 % was caused by the harvester is within acceptable limits when compared to other harvesting methods.

RECOMMENDATIONS

- Mechanical cassava harvesting, far from being perceived as grandiose technology push academic exercise, the field test results generated new ideas that would lead to modern practices in cassava production. This calls for strategic thinking, sustained research programme development, sound human resource management and prudent financial mobilisation.

- Instead of waiting for users to reach the level of the requirements of a technology, mechanical cassava harvesting technology that is new on the African continent and at the level of users' needs and resources should be introduced, demonstrated and promoted. Over the medium and long term, the harvester project will need the constant support of committed research and development systems. Creation, strengthening and integration of this technology research and development system within the continent's
cassava project should be contemplated in the continent’s cassava promotion strategy.

- Since majority of farmers on the continent plant cassava on the flat and as a mixed crop using conventional tillage practices, it will be necessary to evaluate harvesting on the flat and with conservation agricultural practices to compare performance and economic analysis of the harvester.

Social impact of any large scale industrial use of cassava in producing communities and its effect on the dietary habits of the farmers.

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