Development and Performance Evaluation of a Small-scale Maize Harvester for Developing Countries

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Authors’ contributions

This work was carried out in collaboration among all authors. Authors JHV, EAA and GCB designed the study, wrote the protocol and wrote the first draft of the manuscript. Authors JHV and VKC performed the statistical analysis and managed the analyses of the study. All authors read and approved the final manuscript.

ABSTRACT

A small-scale maize harvester was designed and fabricated for developing countries and is composed of a harvester header, a chain conveyor, a drive power unit and a five-wheel tricycle. Fabrication of components was made and assembling of the devices on the tricycle was done. The performance evaluation of the small-scale maize harvester was done at 15% kernels moisture content (wet basis). Three rotational speeds of the engine, 1347, 1521 and 1937 rpm were used, while the forward velocity of the harvester was kept at an average of 0.617 km.hr⁻¹. The testing experiment revealed significant effect of physical properties of maize (p<0.05). The highest machine capacity was obtained at 0.05 ha.hr⁻¹, while the highest driving efficiency was 97.30% and the highest picking and conveying efficiencies were 84.11% and 98.21%, respectively. However, it was
observed that the machine noise level decreased with increase in engine speed. Also, the engine speed affected both picking and conveying efficiencies. The designed machine is found suitable for most smallholder farms.

Keywords: Maize harvester; chain conveyor; ear-picker; conveying efficiency; tricycle.

1. INTRODUCTION

Sub-Saharan African economies are mostly based on the agricultural sector. In the particular case of Benin Republic, this sector represents 35% of its Gross Domestic Product (GDP) and employs 70% of the active population [1]. According to MAEP [2], among cereals, maize (Zea mays L.) is the most produced with 1.345 million tons in 2013 against 1.691 million tons of whole cereals produced. This performance is linked to the importance of maize in Benin culture, culinary habit and to the actions in favour of the mechanization in the sector. Indeed, in Benin, research innovations and political actions in maize mechanization are rather to emphasize on pre- and post-harvest operations than harvesting. Actually, the government has imported several farm machineries such as tractors and other equipment such as, seeders and sprayers to improve production of crops including maize [2]. These machines which are intended for pre-harvest activities are used to increase the area of land cultivated and to reduce the labour requirement in production period. Moreover, the National Institute of Agricultural Research of Benin (INRAB) has developed and improved some post-harvest practices and technologies for maize storage and processing. Among these technologies, threshers, winnowers, calibrators and huskers were introduced throughout the territory to increase the quantity and the quality of products and by-products of maize [3,4]. However, between the development of pre-harvest and post-harvest mechanization, the maize harvesting remains traditional.

In usual practice, maize harvesting is done manually, and ears are collected in burlap bags. This method does not require any specific tool but involves high labour requirement. Labour is provided by women and children, who are not normally involved in ridging. In fact, traditional maize harvesting is time consuming from 25-30 days per hectare [5] and it is done in a bending posture. Furthermore, maize harvesting period affects both its quality and harvesting efficiency [6]. As it has been argued by Kim [7], if harvesting is delayed because of climate or hybrid maturity, maize yield and quality may decrease due to microbial infection or frost damage. These difficulties involve low harvesting capacity, crop quality, financial return and high labour requirements.

Since harvest mechanization offers farmers the opportunity to expand production volume, quality and reduces costs per unit and labour hours for harvesting [8]; it can help to attenuate the effects of traditional harvesting difficulties and improve maize production in Benin. In addition, the purpose of mechanized maize harvesting is to replace manual labour to harvest maize from fields in time with a minimum loss while maintaining a high quality.

Thus, the aim of this study was to develop and evaluate the performance of a small-scale maize harvester usable for farmers in developing countries especially maize farmers in Benin Republic.

2. MATERIALS AND METHODS

2.1 Design Considerations

2.2.1 Harvester rolls parameters

The theoretical harvester speed was determined by equation 1:

\[ v_h = \frac{L_pt \cdot Ch}{3600 \cdot h_h} \]  \hspace{1cm} (1)

Where,

\( v_h \) = harvester speed, \( m \cdot s^{-1} \);
\( L_{pt} \) = total length of the plantation per ha, \( m \cdot ha^{-1} \);
\( C_h \) = theoretical
hourly capacity of the harvester, ha·hr⁻¹ and \( \eta_{th} \) worse theoretical harvester field efficiency, %.

The interaxial distance between rolls was determined according to the expressions described by Miu [9]:

\[
a_r > d_a + d_{pt} + \frac{d_{pt}}{\cos(a_r)} \tan(\gamma_t) \quad 2(a)
\]
\[
\tan \gamma_t < \mu_{sr} \quad 2(b)
\]

Where, 

\( a_r \) = interaxial distance between rolls, mm; \( d_a \) = diameter of roll cone end, mm; \( a_c \) = inclined angle of rolls, °; \( d_{pt} \) = mean plant diameter, mm; \( \gamma_t \) = half angle of the roll cone, ° and \( \mu_{sr} \) = coefficient of dynamic friction between the plant stalk and the roll surface.

The diameter of the rolls was determined according to equation 3 developed by Miu [9]:

\[
D_r \geq \frac{\psi_d d_{pt}}{1 - \left[ \frac{4 - \left( \frac{\psi_d}{\delta_r} \right)^2}{1 + \left( \frac{\psi_d}{\delta_r} \right)^2} \right]^{\frac{1}{2}}} \quad 3(a)
\]
\[
\psi_d = 1 - \frac{\delta_r}{\delta_{pt}} \quad 3(b)
\]

Where: \( D_r \) = diameter of rolls, mm; \( \psi_d \) = relative deformation of maize stalks, dimensionless and \( \delta_r \) = thickness of deformed stalk by rolls, mm

The minimum angular speed of rolls was computed according to the mathematical expression 4 proposed by Miu [9].

\[
\frac{S_{pt}}{v_h} \geq \frac{2\pi}{\omega_r} \quad 4
\]

Where: \( \omega_r \) = angular speed of rolls, rad·s⁻¹ and \( S_{pt} \) = average space between two consecutive plants on the row, m

Whereas the length of the rolls was found using equation 5 developed by Miu [9]:

\[
l_r \geq \frac{v_h(h_{pt} - h_r)}{v_r(1 - \varepsilon_d \cos^2(a_r) + v_r \sin(a_r))} \quad 5
\]

Where: \( l_r \) = length of the rolls, m; \( h_{pt} \) = average maize plants height, m; \( h_r \) = elevation height of rolls axle from ground, m; \( \varepsilon_d \) = coefficient of slippage of the stalk relative to the rolls, dimensionless and \( v_r \) = stalk drawing velocity, m·s⁻¹.

The required minimum diameter, length and angular speed of rolls were found to be 0.75 m, 51.22 mm and 35.31 rad·s⁻¹ respectively.

### 2.2.2 Power requirement on the harvester rolls

During the stalk drawing, the ear peduncle breaks and the ear is pushed backwards by a chain mug. The conveying force is given by the developed equation 6:

\[
f_c > (l_{ch} \cdot \psi_{ch} + u \times w_e) \cdot g \cdot \sin(a_r) \quad 6
\]

Where: \( f_c \) = conveying force in snapping chains, N; \( u \) = maximum number of ears conveyed per snapping chain, unit; \( \psi_{ch} \) = specific weight of the chain, kg·m⁻¹; \( l_{ch} \) = snapping chain length, m; \( g \) = gravitational acceleration, N·kg⁻¹ and \( w_e \) = ear weight, kg.

The power requirement of rolls of the harvester is given by the equation 7.

\[
P_{rh} = 2(\tau_r \cdot \omega_r + f_c \cdot v_{ch}) \quad 7
\]

Where: \( P_{rh} \) = power requirement on the harvester rolls, W.

The required conveying force was found to be 55 N and the power on the harvester rolls was 4.25 kW.

### 2.2.3 Power requirement of the conveyor

The chain tension force is given by the equation 8 proposed by Sumpf et al. [10]:

\[
F_n = F_{RS} + F_g \cdot \sin(a_c) + F_{n-1} \quad 8(a)
\]
\[
F_g = g \cdot L_c \cdot (q_K + q_o) \quad 8(b)
\]
\[
F_{RS} = \mu_c \cdot g \cdot L_c \cdot (q_K + q_o) \cos(a_c) \quad 8(c)
\]
\[
F_n = g \cdot L_c \cdot (q_K + q_o) \mu_c \cdot \cos(a_c) + \sin a_c \cdot F_{n-1} \quad 8(d)
\]

Where: \( F_n \) = chain tension force of conveyor, N; \( F_{n-1} \) = chain take-up tension, N; \( F_g \) = force due to gravity, N; \( F_{RS} \) = frictional force, N; \( a_c \) = slope angle of conveyor with horizontal plane; \( \mu_c \) = friction coefficient, dimensionless; \( q_K \) = specific weight of the chain, kg·m⁻¹; \( q_o \) = specific weight of
the good (maize ear), kg·m⁻¹ and \( L_c \) = length of the conveyor, m.

The chain take-up tension can be determined by using the equation 9 proposed by Fayed, Skocir [11]:

\[ F_{n-1} = 2\mu_c \cdot g \cdot L_c \cdot q_k \cdot \cos(\alpha_c) \]

9(a)

\[ q_c = \frac{w_c}{d_c} \]

9(b)

Where: \( d_c \) = average diameter of maize ear, m

The power requirement of the conveyor was determined following equation 10 proposed by Fayed, Skocir [11]:

\[ P_{rc} = (F_n - F_{n-1}) \cdot v_{cc} \]

10

Where: \( P_{rc} \) = conveyor power requirement, N and \( v_{cc} \) = conveyor chain speed, m·s⁻¹

The required chain tension and take-up tension forces of the conveyor were found to be 189.42 N and 60 N, respectively, while the power requirement of the conveyor was 0.157 kW.

2.2.4 Calculation of gears speed of the harvester header gearbox

The harvester header gearbox was a double right-angle gearbox with one (1) input and four (4) outputs. It must be able to animate the two axles of rolls and the two sprocket axles of snapping chains as shown in Fig. 1. Each roll axle (2,3) and sprocket axle (6,7) rotate symmetrically with their second.

The speed and number of teeth of each gear used are shown in Table 1.

![Fig. 1. Kinematic diagram of the harvester header gearbox](image-url)
### Table 1. Speed and number of teeth of gears

<table>
<thead>
<tr>
<th>Number of teeth</th>
<th>Speed (rad·s⁻¹)</th>
<th>Speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_a = 28$</td>
<td>$\omega_a = \frac{Z_b \cdot \omega_b}{Z_a}$ = 16.07</td>
<td>$N_a = 153.47$</td>
</tr>
<tr>
<td>$Z_b = 10$</td>
<td>$\omega_b = \omega_e = 45$</td>
<td>$N_b = 429.72$</td>
</tr>
<tr>
<td>$Z_c = 10$</td>
<td>$\omega_b = \omega_e = 45$</td>
<td>$N_c = 429.72$</td>
</tr>
<tr>
<td>$Z_d = 21$</td>
<td>$\omega_d = \frac{Z_a \cdot \omega_a}{Z_d}$ = 21.43</td>
<td>$N_d = 204.63$</td>
</tr>
<tr>
<td>$Z_e = 21$</td>
<td>$\omega_e = \frac{Z_a \cdot \omega_a}{Z_e}$ = 21.43</td>
<td>$N_e = 204.63$</td>
</tr>
<tr>
<td>$Z_f = 33$</td>
<td>$\omega_f = \omega_d = 21.43$</td>
<td>$N_f = 204.63$</td>
</tr>
<tr>
<td>$Z_g = 33$</td>
<td>$\omega_g = \omega_e = 21.43$</td>
<td>$N_g = 204.63$</td>
</tr>
<tr>
<td>$Z_h = 20$</td>
<td>$\omega_h = \omega_{ch} = 35.36$</td>
<td>$N_h = 337.64$</td>
</tr>
<tr>
<td>$Z_i = 20$</td>
<td>$\omega_i = \omega_{ch} = 35.36$</td>
<td>$N_i = 337.64$</td>
</tr>
</tbody>
</table>

#### 2.2.5 Flexible transmission features calculations

Calculations of the flat and V-belt features was done using equations proposed by Khurmi, Gupta [12].

**Flat belt transmission features calculations**

The length of the flat belt is given by the equation 11:

$$ L_{12} \approx 2C_{12} + \frac{\pi}{2}(D_1 + d_2) + \frac{1}{4C_{12}}(D_1 + d_2)^2 (11) $$

Where: $L_{12}$= Total length of the belt, mm; $C_{12}$= Distance between the centres of two pulleys, mm; $D_1$= Driven pulley diameter of main shaft of the chain conveyor and $d_2$ = Drive pulley diameter of main shaft of the harvester gearbox.

The width of the belt is calculated based on the equation 12:

$$ b_{12} = \frac{r_{12}}{t_{12} \sigma_{12_{max}}} $$  \hspace{1cm} (12(a))

$$ T_{12} = T_2 + T_{c_{12}} $$  \hspace{1cm} (12(b))

$$ T_{c_{12}} = m_{12} \cdot V^2_{12} $$  \hspace{1cm} (12(c))

$$ m_{12} = \rho_{12} \cdot b_{12} \cdot t_{12} \cdot L_{12} $$  \hspace{1cm} (12(d))

Where: $b_{12}$ = Belt width, m; $\sigma_{12_{max}}$ = Maximum working tensile stress, N.m⁻²; $t_{12}$= Belt thickness, m; $T_{12}$= Maximum tension in the belt, N; $T_{c_{12}}$= Centrifugal tension of the belt, N; $T_2$= Tension in the tight side of the belt, N; $T_{c_{12}}$= Centrifugal tension of the belt, N; $m_{12}$= Mass of belt per unit length, kg·m⁻¹ and $\rho_{12}$= Belt density, kg.m⁻³.

The length and width of the flat belt were found to be 925 mm and 20 mm, respectively, for a chosen belt thickness of 9.5 mm.

**V-belt transmission length**

The length of the V-belt is given by equation 13:

$$ L_{34} \approx 2C_{34} + \frac{\pi}{2}(D_3 + d_4) + \frac{1}{4C_{34}}(D_3 - d_4)^2 (13) $$

Where: $L_{34}$= Total length of the V-belt, mm; $C_{34}$= Distance between the centres of two pulleys, mm; $d_4$= Driven pulley diameter of main shaft of the harvester header gearbox, mm and $D_3$ = Drive pulley diameter of out shaft of the harvester gearbox, mm.

The required length of the V-belt was found to be 2990 mm.

#### 2.3 Test Procedure

Experiments were conducted in order to assess the field performance of the small-scale maize harvester. During the study, the preliminary experiments were performed at the School of Rural Engineering (EGR), National University of Agriculture (UNA), Kétou in Benin Republic. They were conducted on local variety of maize crop at Kadjola village, Kétou.

A field of 6 rows of 12 plants was taken for conducting each experiment. The density of maize plants present in the test field was 0.8 m x 0.4 m. Before carrying out the experiment, the moisture content, ear density and ear position were measured. During the experiment, the operating parameters such as the total times (operative and non-productive), fuel consumed
and noise levels were also measured according to Philippine Agricultural Engineering Standard PAES [13]; whereas, forward speed of the tricycle was kept 0.612 km‧hr⁻¹ for the harvesting. After the machine test, number of unpicked plants and ears loss were registered.

The small-scale maize harvester was tested using field operational pattern as recommended by PAES [13]. The crop was harvested at 135 days after sowing. The whole experiment was replicated three (3) times by varying the drive engine speed at 1347, 1521 and 1937 rpm, respectively. Measurement was done using digital laser tachometer, digital timers, tape measure, Vernier calliper (200mm, ±0.05), digital no1qaise level meter and graduated cylinder.

2.4 Performances Evaluation

The experimental parameters recorded were used for the computation of performances of the small-scale maize harvester. Among those computed performances were the actual and theoretical field capacity, the field, picking and conveying efficiency and the fuel consumption rate. This was done in accordance with Philippine Agricultural Engineering Standard (PAES).

The PAES PAES [13] formulae were used for the computation of the actual field capacity, theoretical field capacity, field efficiency, picking efficiency, conveying efficiency, total machine efficiency, fuel consumption rate and the moisture content as developed in equations 14 to 23, respectively.

Actual field capacity

\[ C_{FA} = \frac{A_T}{T_{op}} \]  
(14)

Where: \( C_{FA} \) = actual field capacity, ha‧hr⁻¹; \( A_T \) = area covered during test, ha and \( T_{op} \) = total operating time, hr.

Theoretical field capacity

\[ C_{FT} = \frac{A_T}{T_{nprod}} \]  
(15)

Where: \( C_{FT} \) = Theoretical field capacity, ha‧hr⁻¹ and \( T_{nprod} \) = non-productive operating time, hr.

Field efficiency

\[ E_F = \frac{C_{FA}}{C_{FT}} \times 100 \]  
(16)

Where: \( E_F \) = field efficiency, %.

Picking efficiency

\[ E_P = 100 - L_P \]  
(17)

\[ L_P = \frac{N_{und}}{N_{py}} \times 100 \]  
(18)

Where: \( E_P \) = picking efficiency, % ; \( L_P \) = picking loss, % ; \( N_{und} \) = number of maize ears undetached from stalk after picking operation, unit and \( N_{py} \) = potential yield, unit

Conveying efficiency

\[ E_c = 100 - L_c \]  
(19)

\[ L_c = \frac{N_{unc}}{N_{py}-N_{und}} \times 100 \]  
(20)

Where: \( E_c \) = conveying efficiency, % ; \( L_c \) = conveying loss, % and \( N_{unc} \) = number of uncollected detached corn ear during operation, unit

Total machine efficiency

\[ E_{TM} = L_P \times L_c \times 100 \]  
(21)

Where: \( E_{TM} \) = total machine efficiency, %

Fuel consumption rate

\[ F_r = \frac{F_c}{T_c} \times 100 \]  
(22)

Where: \( F_r \) = fuel consumption rate, L‧hr⁻¹ ; \( F_c \) = amount of fuel consumed, L and \( T_c \) = engine operating time, hr.

Moisture content

\[ M_{Cwb} = \frac{W_f-W_i}{W_i} \times 100 \]  
(23)

Where: \( M_{Cwb} \) = moisture content, % ; \( W_i \) = initial weight of the sample, g and \( W_f \) = final weight of the sample, g.

3. RESULTS AND DISCUSSION

3.1 Fabrication and Assembly

The machine was designed using Topsolid Software version 7.11 based on the kinematic diagram shown in Fig. 2 and the design is shown in Fig. 3.
The small-scale maize harvester is an assemblage of harvester header, chain conveyor and drive unit on five (5) wheels tricycle cargo as illustrated in Plate 1. The assembling order is the installation of the chain conveyor, the harvester header and the drive unit in that order on the tricycle.

The drive unit consists of the 6 hp diesel engine with a nominal speed of 2,400 rpm, 100 mm diameter pulleys on the engine and secondary gearbox shafts, B98 V-belt (2,565.4 mm circumference). The belt transmits power from the engine to the secondary gearbox input shaft. Its tension is adjustable by moving the engine over the engine frame groove. The secondary gearbox is a right-angle drive made on worm gears with a transmission ratio of 1 to 5. The drive unit also consists of a double B97 V-belt (2,540 mm circumference) which transmits power from the output shaft of the secondary gearbox to the input shaft of the harvester header gearbox. This input shaft is driven through 210 mm diameter pulley. The belt tension is regulated through an adjustable belt tensioner. Flanged pulleys with 80 mm and 100 mm diameters, on
respectively the input shaft of the harvester header gearbox and the drive shaft of the chain conveyor, are rotated through a crossed 5PK1225 flat belt (5 plies and 1225 mm circumference).

The harvester header is an assemblage of harvester header gearbox, harvesting rolls, snapping chains, snapping plate and cover. The covers were made on 1 mm steel sheet and its shape was made by bending and welding. The snapping plates were made of 5 mm steel sheet. They were welded to the harvester header gearbox front face and support the harvester rolls end through an even pillow block bearing unit (P 204). The snapping chains were made of 14.25 mm chains pitch, two sprockets of 15 teeth and five welded mugs (reinforced 5 mm steel sheets) with regular spacing of 584.25 mm. Also, the harvesting rolls were fabricated based on 60 mm diameter steel pipe with 5 mm wall thickness. Their extremities were welded with 150 mm length cone augers having 100 mm pitch, 15 mm depth and 6 mm thickness.

The harvester header gearbox is an assemblage of bevels and helical gears with shafts mounting in a carter. The gearbox carter is made of 5 mm steel sheet which is reinforced by 10 mm steel sheet at each bearing roller position. The main shaft is made by cutting 55 mm diameter round steel bar on the lathe machine. The key grooves of the shaft ensure positive fitting of installed bevel gears (28 teeth, 5 mm module) and pulleys. The horizontal bevel pinions (10 teeth, 5 mm module) were made by cutting 70 mm round steel bar on the lathe machine and horizontal milling machines. Helical gears (3 mm module) were installed with vertical bevel pinions (21 teeth, 5 mm module) in their shafts and bearing roller, respectively. All the mobile elements are lubricated using grease lubrication method and assembly to allow easiest access to control and to feed the gearbox from its back face.

The chain conveyor consists of two synchronous drive chain mechanisms transporting goods (ears) through welded slats. The spacing between slats was 40 cm and 1.5 cm between slat and frame. The conveyor frame is 32° inclined with horizontal plan. The drive shaft is at bottom level and is supported by the frame through two pillows block bearing unit (P 205). The driven shaft is at the top level and supported by two screw tensioners through two flanged block bearing units (F 205). The chain conveyor is installed and bolted on the left side of the cargo tricycle.

Plate 1. (a) harvester header, (b) harvester rolls with (c) Small-scale maize harvester
3.2 Operated Speed of Machine Parts

The analysis of the results shows that the rotational speed for the mobile parts had different values and increased with respect to the increase of the engine speed. For an increase in the rotational engine speed from 1347 rpm to 1521 rpm and to 1937 rpm; the rotational speed of the harvester rolls increased from 360.36 rpm to 404.88 rpm and to 514.92 rpm, while the rotor speed of the conveyor varied from 52.07 rpm to 59.6 rpm and to 75.5 rpm. Also, the linear speed of the snapping chain increased from 0.48 m·s⁻¹ to 0.54 m·s⁻¹ and to 0.67 m·s⁻¹ with respect to the increase of the engine speed. The average forward velocity of the small-scale maize harvester was 0.17 (±0.04) m·s⁻¹. The rotational speed range of the harvester rolls, 360.36 - 514.92 rpm, is approximately the same rolls speed range, 400-600 rpm, reported by Pishgar-Komleh et al. [14] on maize picker-husker. However, the harvester rolls speed range was lower than the rolls speed range, 650 to 800 rpm, reported by Aijun et al. [15] while studying the influence factor analysis of mechanical damage on corn ears picking.

3.3 Crop Conditions at Harvest

The average moisture content (wet basis) of maize kernels in the fields 1, 2 and 3 were 15.20 (±0.45)%; 16.30 (±2.11)% and 15 (±0.50)% respectively. The one-way Analysis of Variance (one-way ANOVA) revealed that there is not enough evidence to conclude that there are differences among the means at the 0.05 level of significance (p-value >0.05).

This indicates that the mean values did not differ significantly and therefore the average moisture content for the whole experiment was 15.50 (±0.34) % wet basis (wb). This value was lower than the design consideration which assumed a range of 20-30% (wb) and can be explained by the harvest delay, 45 days after crop maturity. Moreover, the maize ear/plant ratios were 2.06, 1.58 and 1.42 for fields 1, 2 and 3, respectively. In the same vein, the percentages of lodged plants were 26.92%, 46.15% and 13.26% with an average height of lodging of 92.64 cm, 81.29 cm and 92.23 cm. The average ear densities were 11.61, 8.90 and 8.03 tons/ha for fields 1, 2 and 3, respectively.

3.4 Effect of Engine Speed on Noise Level of the Machine

The effect of the engine speed on noise level of the machine is presented in Fig 4. The trend showed that the noise level decreased with increasing engine speed. The noise level varied from 109.20 to 106.40 and to 105.10 dB with respect to the engine rotation speed of 1347 rpm, 1521 rpm and to 1937 rpm. It could be inferred that the noise level varies inversely with the engine speed. Therefore, the highest engine speed optimized the noise level of the machine. This is in accordance with previous studies which confirmed that noise level varies with engine speed [16] and dominates the acoustic behaviour particularly in part load operation at low speeds [17]. However, the noise level of the fabricated small-scale maize harvester is higher than the maximum allowable noise level for six hours of continuous exposure based, i.e. 90 dB(A), as recommended by PAES [18].

3.5 Machine Capacity and Fuel Consumptions

The field capacities of the maize harvester were 0.04, 0.03 and 0.05 ha·hr⁻¹ for the theoretical field capacity and 0.01, 0.01 and 0.02 ha·hr⁻¹ for the actual field capacity at engine speed of 1347 rpm, 1521 rpm and to 1937 rpm, respectively. This corresponds, following the same order, to 0.29, 0.29 and 0.38 ha·day⁻¹ for the theoretical field capacity and 0.07, 0.06 and 0.08 ha·day⁻¹ for the actual field capacity for 8 hr work per day. Greater field capacities, 0.42 ha·h⁻¹ and 0.73 ha·h⁻¹, were obtained by Pishgar-Komleh et al. [14] while testing a corn picker-husker at a forward velocity of 3.78 km·h⁻¹ and 7.21 km·h⁻¹, respectively. Their results showed that the field capacity increased with the forward velocity as shown by Miodragovic, Djivic [19] who inferred that the feed rate, which is proportional to the forward velocity, affects the machine capacity directly. Therefore, it could be concluded that the low experimental forward velocity (0.61 km·hr⁻¹) is responsible for the low field capacity obtained from the small-scale maize harvester. In fact, the scale of the experiment does not allow to increase in the forward velocity to the maximum acceleration of the machine.

On the other hand, the fuel consumptions were, with respect to the experimentation order, 0.45, 0.44 and 0.78 l·hr⁻¹ of petrol and 0.34, 0.49 and 0.32 l·hr⁻¹ of diesel.
3.6 Machine Efficiency

The driving efficiency was found to be 97.20, 90.24 and 97.30 % for engine speed of 1347 rpm, 1521 rpm and 1937 rpm, respectively. In addition, the picking efficiency was 84.11, 76.83 and 75.68 %, while the conveying efficiency values were 85.56, 90.48 and 98.21%. However, the chain conveyor efficiency was 100%. In fact, in fact, no loss was observed during chain conveying to the cargo. Therefore, the machine conveying efficiency was the same with that of the harvester header. Also, the total machine efficiency was 71.96, 69.51 and 74.32%; respectively. Then, the machine efficiency varied with increase of engine speed. Also, Pishgar-Komleh et al. [14] revealed that the forward velocity has more impact on harvesting efficiency than the rotational speed of the cylinder. More so, Pareek [20] concluded that the forward velocity and the kernel moisture content had significant effect on the picking efficiency and found an optimum picking efficiency of 92% at 25.9% kernel moisture content and at 2.5 km·hr⁻¹ forward velocity. So, it could be assumed that the picking efficiency of the small-scale maize harvester could be improved by acting on the forward velocity and the kernel moisture content by harvesting at the time of maturity of the crops.

3.7 Effect of Physical Dimensions of Maize Ears on Conveying Efficiency

During the experimentation, it was observed that there are maize ear losses during snapping at the level of the harvester header. This loss affects the conveying efficiency of the maize harvester after picking operations. Therefore, one-way ANOVA analysis was done to see whether the ear length means and diameter means are equal for conveyed ears and lost ears at engine speeds of 1347 rpm, 1521 rpm and to 1937 rpm. The result showed that there is not statistical evidence at 5% level of significance to conclude that ear length means are equal, same for the ear diameter means. According to this analysis ear length means are not equal for conveyed ears and lost ears, same for the ear diameter means. Therefore, it could be concluded that the geometrical dimensions (length and diameter) of maize ears affect the conveying efficiency of the harvester header. There is no comparison with previous studies because they are emphasized on grain conveying efficiency than maize ears conveying.

3.8 Effect of Engine Speed on Picking and Conveying Efficiencies

The effect of engine speed on picking and conveying efficiencies is presented in Fig. 5. It reveals that the conveying efficiency and the picking efficiency varied asymmetrically with the increase of the engine speed. It was observed that the lowest picking efficiency (75.83%) and the highest conveying efficiency (98.15%) were obtained at an engine speed of 1347 rpm. However, the highest picking efficiency (84.11%) and the lowest conveying efficiency were obtained at 1521 rpm engine speed. Conversely,
Fig. 5. Scatter plot of conveying efficiency and picking efficiency with engine speed

at an engine speed of 1937 rpm, the conveying efficiency increases (up to 89.09 %), while the picking efficiency decreases up to (76.83 %). It could be inferred that an optimization of the small-scale maize harvester could require an adjustment of the harvester gearbox header such that the actual lowest snapping chain speed (0.48 m·s⁻¹) will be obtained at 1521 rpm engine speed. Shanglong et al. [21] found an optimum ear loss rate at 2.4% (97.6 % picking efficiency) when the speed of snapping rolls was 1100 rpm and the speed of shredding device was 1584 rpm; concluding, therefore, significant effects of the engine speed on picking efficiency.

4. CONCLUSION

A small-scale maize harvester was fabricated. The testing experiment was done at small-scale level and the performance results showed significant impact on the physical and mechanical properties of maize. The following conclusions were made:

- Highest machine capacity was obtained at 0.05 ha.hr⁻¹, while the highest driving efficiency was 97.30% and highest picking and conveying efficiencies were 84.11% and 98.21%, respectively.
- Engine speed affected picking and conveying efficiencies. The optimum picking and conveying efficiencies could be obtained by operating the harvester header gearbox such that the actual lowest snapping chain speed will be obtained at 1521 rpm engine speed.
- Maize ears conveying was influenced by its physical properties (length and diameters). The machine should be used for maize varieties having high potential of maize ears with a least length of 278.43 mm and a least diameter of 51.85 mm.
- Machine noise level decreased with increase of harvester engine speed.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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COMPETING INTERESTS
Authors have declared that no competing interests exist.

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