Design, Construction and Performance Evaluation of Potato Harvesters: A Review

Dessye Belay

Ethiopian Institute of Agricultural Research, Agricultural Engineering Research, Fogera National Rice Research, and Training Center, P.O.Box:1937, Bahir Dar, Ethiopia.

---***---

Abstract : *Potato is the secondary non-cereal crop in Ethiopia, of which around 1,288,146 household farmers depend on it. Potato harvesting was practiced using animal-drawn local Maresha and hand hoe, that characterized by high man-hour requirement, drudgery, and considerable losses in tuber damage and inefficient exposure. The objectives of this paper are to gather information on potato harvesting technologies; focus on the technical developments achieved in digging, picking, and separation devices; highlight the problems still to be solved, and discuss the prospects of potato harvesting technologies. It presents the developments that took place in potato harvesting practices over the last decades in chronological order. All designs and improvements made on the potato digging machines can be concluded on four basic working principles. These are reciprocating, conveying, rotating, spinning, and multi-purpose operating principles relative to the forward motion of the power source. Hence, the potato digging machine available now can be grouped into the following mechanism. These are rotor conveying, rotary blade, reciprocating/vibrating, multipurpose, and spinners/slashing harvesters. Based on power source it can also be grouped into manual, animal-drawn, tractor-drawn, and self-propelled combine harvesters. Besides, there are a tractor operated and a self-propelled potato combine harvester. Moreover, potato combines harvesters may be divided into straight thru and the windrower harvester. The straight-thru is a more efficient harvester, in sandy soils; however, windrows are simplified harvester, which can be self-propelled or tractor drawn that is efficient for sandy soil having a folding vine cutter. Improvements undergoing right now are design improvements based on size, power source, blade shape, blade angles, speed of operation, ridge opening device, and other accessories and evaluating the performances of the machine.*

Keywords: Design, construction, evaluation, potato tuber, digger

1. Introduction

Potato (*Solanum tuberosum L.*) is the fourth most important food crop in the world [1]. It provides higher nutrition and an adaptive species for climate change. It is used mainly for human food, animal feed, and manufacturing starch, alcohol, and fermented beverages including beer. Apart from their high water content, this crop contains mainly carbohydrates (largely starches that account for 16-24% of the total weight) with very little protein and fat (0-2% each) [2]. Ethiopia, produces potatoes on 160,000 ha with an average yield of 10 t/ha so the national production is 1.6 million tons in the 2011/12 cropping season [3]. Potato is important food security and a hunger reliever crop in several parts of the country under its ability to mature earlier than most other crops at the time of critical food need. In recent years, the production of this crop is expanding rapidly owing to the presence of improved technologies and the expansion of irrigation culture [4]. Improvements in the potato production system can be a pathway out of poverty in Ethiopia. It is an excellent smallholder farmer crop in the highlands, and serves as both a cash and food security crop. It is a high-yielding tuber crop with a short cropping cycle of about 3-4 months. It is a high yielding (about 40 t/ha) tuber crop with a short cropping cycle of about 3-4 months. This makes potato a suitable crop for places, where land is limited and labor is abundant [5].

Ethiopia's rapidly expanding population is explaining that roots and tubers are estimated to provide 20% of per capita daily calorie intake than in sub-Saharan Africa. Despite being grown on only 0.21 million ha (1.4% of the cultivated area) in Ethiopia, root crops provide 10.3% of overall crop production (4.2 million ton) [6]. Based on the agricultural sample survey, root crops production in the period 2014/2015 cropping season was more than 5.5 million ton which is about 15.13% of the total annual agricultural production of Ethiopia. From 216,971 ha of land, potatoes accounted for 81.74%. In terms of production, also it is 83.66%, of the total root crop [7]. Potato for rural and urban markets is harvested by hand. The staple roots grown beneath the soil are likely to suffer a mechanical injury at harvest because of digging by traditional tools. Manual harvesting is the traditional method of harvesting using a hoe, cutlass, or mattock to dig around the standing stem to pull out the roots by detaching the uprooted roots from the base of the plant. Manual harvesting requires about 22-62 man-days per hectare [2]. The post-harvest loss of potatoes in Ethiopia is more than 25%, which includes losses during harvesting [8].

The mechanization of tuber harvesting has passed several stages. The earlier equipment used, primarily for splitting or breaking of the ridges, exposing the tubers required expeditious picking of tubers. From simple animal-drawn diggers to modern, sophisticated crop harvesting machines have been developed after the Second World War [9]. To clarify the attempts made to design and evaluate appropriate potato harvesting technology and the possibility to adapt suitable technologies for these small farm holders, but the major contributor of the sector in the country, a better understanding of previous technology and the recent review is the starting point. On the other hand, to help researchers and policy-makers by providing an overview of ongoing development on potato harvesting machinery and related science and engineering innovations for the potential food security implications at the household level. Hence, this paper reviews various design strategies in digging, picking, and separation systems, as well as developments in potato harvesting machinery during the previous years in several countries. There are several review papers available, but this paper is in an updated form that can provide an insight into design methods and developments in potato harvesting technologies available throughout the world.

The main objectives of this paper are to gather the necessary information on potato harvesting mechanization technologies; focus on the technical developments so far achieved in digging, picking, and separation mechanisms, technical performance evaluation and assessment of the parameters, optimum condition, highlight the problems still to be solved and discuss the prospects of potato harvesting technologies.

2. Timeliness of Harvesting

Potato harvesting is chronological and critical work to be performed in time. The stage of harvesting can be a cause of poor product quality and rapid deterioration thereafter is harvesting immature. It should be harvested when the vines turn yellow [10]. In Ethiopia, potato harvesting is determined based on the drying of foliage, the vegetative cycle of the varieties planted, and observations of tubers. Ready for harvest may be determined by the physiological maturity of the crop when leaves acquire yellow color become brittle and dry off. Between 15 to 20 days after the plant is completely dry was recommended for consumer and commercial us [11].

For seed potato production, premature harvest is advisable to accelerate the process of maturity through foliage elimination that accelerating the process of maturity through foliage elimination [12]. Ware potato should be harvested when the crop attain matured tuber, dried up foliage, and firm tuber's skin. On the other hand, haulm cutting should be done between 10-14 days before harvesting to develop thick tuber skin and reduce harvesting damage. Stop irrigation about two weeks before haulm removal is critical [4]. After haulm cutting, the harvesting of tubers should be finished within 10-15 days. Delay in harvesting beyond these days will increase disease infection and tuber rotten. Rainy day potato harvesting is also increasing the tuber rotten [13]. Potato tuber should be dug out when the skin of a tuber is stronger using the appropriate tools to minimize damaged tubers [4].

3. Design Factors of Potato Harvester

Research findings have typically shown factors that influence the level of potato tuber damage during harvest were soil type, soil temperature, the maturity of the crop, crop variety, harvester design, and harvesting conditions. The apparent magnitude and a considerable extent of mechanical damage caused by agricultural products were also varied naturally depending on the engineering property, the unique structure of the product, nature, and the appalling magnitude of the external forces [14].

3.1. Physical properties of potato tuber

The physical possessions of agricultural products are the parameters to be considered in the design of digging, lifting, grading, conveying, processing, and packaging systems. Among these physical properties, size, shape, mass, volume, density, and projected area are the most important properties to design agricultural machinery. The frictional properties such as angles of repose and coefficients of friction are other important parameters to be considered in designing agricultural machines for harvesting, conveying, separating, sorting, handling, processing, etc. [15, 16]. The major moisture-dependent physical properties of biological elements, amendable to change within a short period (transient physical properties) are also shape, size, mass, bulk density, true density, porosity, and static friction coefficient [17].

Broadly, the engineering properties of agricultural materials and food products are important in many grains/seeds, vegetables, and food materials handling and processing operations. Rapid and accurate determinations of physical properties are needed in processing agricultural materials [18, 19, 20]. The skin surface of the potatoes is susceptible to abrasion and exposed to physical damage during harvest and post-harvest procedures. Practical knowledge of the abrasion resistance of raw potato is important information, particularly during mechanical harvesting [21].

3.2. Soil Parameters

The soil naturally has a diverse set of fundamental properties. Hence, the empirical and theoretical study of soil mechanics has to be gratefully considered during the design of mechanical and structural types of modern machinery. An important component of the potato digger is the share/blade and a conveyor. The blade is engaged in the soil to dig up the potato tubers and carefully transfer them to the conveyor. Hence, the soil parameters play an important role in designing the potato digger [23]. Soil parameters including moisture content, bulk density, penetration resistance, shear strength; aggregate size distribution, and proper angle of soil-metal friction are critical factors that should be positively identified in designing potato-harvesting machines. Soil temperature and soil moisture contents of individual fields have varied from place to place because of water and organic matter, content, texture, slope, and localized environmental factors [24]. The moisture content (db.) of sandy loam soil should be between 6.7-10% [11, 25]. Similarly, most potato field soils during harvest are recommended to be 11 -15% dry base moisture content for minimum damage [26, 27].

Soil moisture content can be evaluated through soil samples taken to a desired depth of the cut. The bulk density of the soil is also determined typically using a bulk density kit. Samples should weigh and keep in the oven at 105 ± 5 °C for 24 hours [23]. Similarly, the soil tool adhesion varies considerably with soil moisture, and then the largest contribution to the draft is from the cohesion of the soil, which is influenced by soil moisture. When sustainably harvesting the root crops, it is very important to properly maintain the soil in a loose state to improve the quality of the separation [28]. A model on the agricultural soil shear strength concluded that soil-water characteristics can determine soil behavior. It predicted a tool width-depth ratio of five, operating at 150mm depth and 40° rake angles, the draft of the tool increased to 2 kN up to 15% moisture content, whereas the draft increased to 5.5 kN when the soil moisture was reduced to 13% [29]. On the other hand, the best tubers-soil temperature during harvest must be between 45 and 65°F [25].

The estimation of soil strength indices is a prerequisite for the design of soil cutting machinery, foundations, retaining walls, and many other engineering interventions. There are several methods to investigate the shear strength of the soil. Some are laboratory methods; others are *in situ* (field) prevalent methods. Laboratory methods include the unconfined compression test, direct shear tests, and triaxial compression tests [30]. While *in situ* method are the vane test, standard penetration test, and penetrometer tests. The field vane is the *in-situ* determination of the undrained strength of the soil. The unconfined compression test can be used to investigate only cohesive soils, whereas the direct shear test and the triaxial compression test can be used to properly investigate both cohesive and cohesionless soils. A vane test can be used to investigate miry clays, exceptionally sensitive clays. The standard penetration test is limited primarily to cohesionless soils, whereas the Penetrometer test is used mainly in fine-grained soils [31]. The soil penetration resistance can be assessed before harvesting using a cone Penetrometer. A cone Penetrometer should be pushed into the soil up to the desired depth with both hands by involving similar force on both grips; hence, soil cone index or resistance to penetration can be evaluated [32]. Although soil shear strength is influenced by cohesion and angle of internal friction [33].

The angle of soil-metal friction is measured on soil block by utilizing the inclined plane method to determine adhesion resistance. Temporarily estimation of surface soil aggregates-size distributions is required to evaluate the soil clod size and level of soil pulverization to separate tubers from the soil. Soil aggregation is expressed by soil mean weight, diameter (SMWD), and a soil pulverization ratio [23]. The pulverization level of the soil clod size between the soil grades is affected by the soil sample left on each soil sieve. Mean weight, diameter is equally determined through the standard dry-sieving method [33, 34].

3.3. Machine Based Factors

Agricultural products including tubers and bulbs are usually exposed to forces during harvesting. Mechanical harvesting strongly affects the quality of potato, mainly in terms of tuber damage that need to investigate the dynamic interaction between the harvesting machine and tubers. Hence, understanding the mechanical characteristics of potato tubers may improve harvest and postharvest operations and reduce economic losses [35]. Mechanical impact, during harvesting and postharvest processes, causes external as well as internal damage to agricultural products. Tuber damage, or bruise, has generally been divided as shatter bruise (externally visible) and blackspot bruise (internal cracking, crushing, and discoloration). The main machine parameters that influenced the performance of the root crop harvester were the design condition of the machine that related to forward speed, rake angle, and blade geometry; operating depth, conveyor oscillation amplitude, conveyor frequency, conveyor speed, and conveyor slope [36].

3.3.1. Slope and speed of the conveyor

The slope and speed of the Conveyor of the elevator and oscillatory harvesters have a significant effect on the performance of harvesters during harvesting. Some literature recommended different optimum values of thus harvesters. Some recommended that should not be more than 15° [2, 37]. Others indicated that the elevator slope of potato diggers should be between 10-20° [10, 38]. A significant and consistent increase in tubers lifting percentage was recorded due to an increase in conveyor inclination from 15-20° for chain conveyor type potato diggers [39]. Also, the semi-trailing root crop conveyor harvester running speed of conveyor canvas was 1.2m/s, with a slope angle of 15° for best performance [40].

On the other hand, a *tef* grain and chaff separating and cleaning machine through an adjustable inclined conveyor sieve mechanism, due to the greater force $(mg \sin a)$ were acting on the entire material down the slope and the difference between gravity and inertia component of forces ($mg \sin a < m\omega^2 r$) led to sliding rather than tossing and bounding when the slope of separating conveyor sieve increases 5° to 10°, which decreased the separation efficiency of a machine [41]. The effect of inclination and speed conveyor chain related to two rows Turnill potato harvester at Fiat tractor (2-WD) with the engine power of 120 HP was also recommended 15° chain inclination [27]. Hence, slope and speed of conveyor should consider seriously during any design, construction, and performance evaluation of potato harvesters.

3.3.2. The rake angle and blade geometry

The rake or approach angle of the tool and the tool shape significantly affected the draft and the harvesting efficiency of mechanical harvesters [42]. Scholars showed different outputs of rake angle value and blade geometry that reviewed in detail herewith. At a rake angle of 14°, the actual field capacity of 0.23ha/h is the least loss and high harvesting efficiency for potato diggers [38]. Although increasing the rake angle to 15°, the soil disturbance area was significantly increased as much as 47% for blade subsurface tillage implements [43]. The other evaluated digger elevator blade angle to be 23° for best performance [44]. On the other hand, the minimum draft and maximum pulverization of soil were at a constant rake angle of 20° [45]. Besides, the performances of lifting blades for different potato harvesters were at rake angles of 20° [46]. As a result, the lift angle of tiller blades observed that a low lift angle (rake angle) accelerated soil cutting and higher lift angles accentuated the upheaval of soil around the tool and hence, soil shattering was satisfied at a higher lift angle of 35° for dry and brittle soils [47]. Another study revealed that the minimum draft occurred at a lift angle of 25° for shallow tillage tools [48, 49].

The studies on the draft force showed that the behavior of wider cutting blades, and then the draft was minimum at a lift angle of 20° [50, 51]. Hence, the optimized blade lift angle of 20° is the minimum draft. A failure model consisting of a straight rupture plane starting from the cutting edge of the soil surface and concluded that the draft force was minimum at a lift angle of 20° [52-56]. Although, the performance of a soil working tool depends on its shape, orientation during movement, and initial soil conditions. The draft force of a soil working tool is directly proportional to the tool width and increases exponentially with operating width. Also, the analytical study of the interaction between the blades of a hoe inclined at less than 25° concludes that at rake angles of less than 20°, the sliding was better [57]. Inclined blades at various rake angle in a glass-sided box and measured the forces on the blade and observed that the draft had a direct relationship with the rake angle and depth [58]. Similarly, the draft increased at a lesser rate up to 20° rake angle and increased drastically beyond 20° rake angles. Others reported that the draft force on tools increased with tool speed [59].

Besides, lateral soil movement and ridge height were affected by both tools, operating speeds at which the faster speeds and steeper rake angles also created larger ridges [60, 61]. The performance evaluation of four different shapes of potato lifting share namely, rectangular, convex, triangular fork, and V-scoop types was carried out on the draft of shares with 500mm width when operating in silt-clay-loam soil at 16% moisture content (db.) and 1.51g/cm^3 bulk density was found maximum with a rectangular shape (1.97kN) followed by convex (1.45kN) triangular fork (1.07kN) and V-scoop share (0.92kN). Also, the field evaluation of shares on an experimental oscillatory sieve potato digger Windrower showed maximum recovery of potatoes at the ratio between oscillation speed to forward speed of travel of 1.38 and was found at 99.23%, 89.80%, 88.01, and 82.48% with V-scoop, triangular fork, rectangular and convex shapes respectively [46].

Broadly, field experiments to evaluate blade performance and tuber damage for the rotary blade system with the depth and draught relationship showed that in silt soil 0.91m diameter of rotary disk blades required 76% less draft than the fixed blade. The draft required for the fixed blade increased significantly with blade depth in deep digging with proper adjustment of attack angle and lateral tilt angle [62, 63]. The performance of blades with different geometry such as straight, convex, concave, triangular, and V-shaped in a lateritic sandy loam soil under uniform soil conditions showed that tools at 25mm and 75mm working depths, the convex tool recorded a minimum specified draft of 2N/cm^2 and 1.76N/cm^2 at the rake angle of 55° [64].

3.3.3. Speed of operation

The other factor during the design of the potato harvester was the forward speed of operation. The various problems of potato damage at harvest, and found out that at higher field speeds during operation of the harvesting machines, the bruise damage of the potato decreased over three years of trials [65]. The recommended field speed of potato harvesting machines was also 2.5-6.5km/h, which typical value to be 4.0 km/h [66]. Average values during normal field operation of the two-wheel tractor were also 3.45km/h. The other designed and evaluated potato digger was with a rotary blade using computer simulation studies and concluded that the optimum forward speed is 1.5-3km/h [67]. Also, a vibratory potato digger's best performance was at a field speed of 3km/h [68]. The study findings in potato harvester performance on tubers by increasing the forward speed of the harvesting machine, the percentage of superficially scratched tubers and broken tubers increased.

Therefore, the total tuber damage and the value of the potato damage index increased. The percentage of lifting potato tubers decreased and the number of potatoes buried in the soil increased when the harvester forward speed increased, then 2km/hr. was the optimum performance [69].

On the other hand, a PTO-driven reciprocating type potato harvester was developed and evaluated at forwarding speeds of 1.80, 2.00, and 2.60km/h with two digger tilt angles of 12^o and 24^{o,} and then lifted tubers were increased with increasing forward, speed up to 6.40 km/h, but 8.60km/h was the least level of lifted tubers as compared to the other forward speeds [70-72]. The optimum conveyor speed of the elevator digger should be nearly the same speed or slightly greater (5 to 10%) than the machine forward speed [73]. Also, recommended the ratio of ground speed to conveyor chain speed to be 1-1.50 to smooth out the flow of tubers through the harvester and reduce tuber damage [74]. Investigation of the effect of forwarding, speed-related to two rows Turnill potato harvester at Fiat tractor (2-WD) with the engine power of 120 HP (51 kW) and recommended the 5.2km/h [27].

3.3.4. Vibration amplitude and frequency

The vibration amplitude and frequency are one essential component to determine the performance of oscillatory potato harvesters. The recommended frequency of most vibratory diggers was 4Hz [46]. The amplitudes, two of vibration increased, potato damage soil, potato losses, and a draft requirement decreased. Hence, vibratory potato digger's best performance was at vibration amplitudes and frequencies of 15-20cm, 4. 5-8 Hz, respectively [68]. An oscillatory potato digger at different frequencies was designed and developed with varying from 0-8Hz and forward speeds from 0.35 to 0.75m/s. The result showed that unexposed and cut tubers were approximately 49.94% and 0.4%, respectively. However, at the oscillation of 8Hz, the unexposed and cut tubers were only about 14.14% and 0.9% respectively [71]. An oscillating potato digger designed and constructed and operated using power tillers and noted that at the amplitude of 12mm and the frequency of 9.67Hz with a travel speed of 0.87km/h resulted in an inadequate operation [72]. Potato harvester for a high percentage of tubers and low damage, the optimum amplitude could be 25mm [75].

When tubers fall from a height of no more than 0.2m, which corresponds to an impact velocity of 1.9m/s and conforms with the acceptable impact velocity of the tubers with the work tools (2.20 m/s) [28]. The investigation of the effect of amplitudes of agitation related to two rows Turnill potato harvester at Fiat tractor (2-WD) with the engine power of 120 HP (51 kW) and recommended zero agitation throw out. Performance of potato harvester on tubers indicated that the primary riddle chain amplitude of 25 mm relatively the best performance [69].

3.3.5. Depth of operation

The best operation depth of cut and moisture content for tractor-drawn potato digger was 15cm and 11.08% respectively [26]. The other study on the average values during normal field operation of the two-wheel tractor was an average working depth of 13.1cm [67]. Also, the optimum operating depth of potato diggers for most types of diggers was 14 cm [46]. Besides, the potato harvester for a high percentage of lifting the tubers with low damage, the optimum-digging depth was 12cm to 22cm [75]. For a potato digger with double chain conveyors during an increase in harvesting (digging) depth, the tubers' lifting goes on increasing, and the cut of potatoes was decreased. On the other hand, the depth of 21cm produced higher scuffed, peeler, severe damage tubers, and total bruised (damage) index of 2.2%, 0.5%, 5.1%, and 43.6 respectively [76]. Another investigation on the effect of the harvesting depth related to two rows Turnill potato harvester at Fiat tractor (2-WD) with the engine power of 120 HP (51 kW) and suggested at 22cm harvesting depth for better performance [27]. The study findings on potato harvester performance on tubers also indicated that digging depth has a highly significant effect on lifted, damaged tuber percentage, and potato damage index. The digging depth of 22cm is the relative best performance [69].

3.4. Crop parameters

The crop parameters include crop variety, maturity of crop/age, moisture content, frictional resistance, static/dynamic component, shear strength, and agronomic behavior of potato tuber, etc. The potato tuber should be planted on a trapezoidal cross-sectional shaped ridge than rectangular ridges for better production [77]. It could be planted on the side of a ridge at a depth of 10-15cm. The distance between plants and rows is 30cm and 60cm respectively is mostly used. The center row spacing becomes narrow (20-30cm) when the product is intended for seed tuber production. Eighteen to twenty quintal seed tubers are required to plant a hectare of land [78]. If the average number of seed tubers in 1kg is more than 18, we can use 18 quintal seed tubers per hectare; whereas if the average number of seed tubers in 1kg is less than 18, we have to use about 20 quintal seed tubers per hectare [79].

On the other hand, the literature suggested 195kg/ha, DAP (NPS), and 165 kg/ha urea fertilizers during planting. The remaining 50% of the urea is applied during flower initiation. Organic fertilizers, farmyard manure, and compost are also other sources of nutrients in potatoes. Potato requires 5000 to 8000m^3 irrigation water per hectare in one cultivating cycle [79, 80]. The most commonly used irrigation method for potatoes is furrow irrigation. Determining the right time to harvest is essential for achieving high-quality produce. Mechanical damage to potato tubers was higher in unfertilized crops and phosphorous was found to provide a favorable effect of reducing mechanical damage to the tubers [81]. The study on two developed cultivars/varieties of potatoes indicated that variety and storage time had undoubtedly been influenced by the mechanical properties of root crops [22].

4. Design analysis of Potato Diggers

4.1. Soil - blade interaction

Soil working tool causes the soil to fail as it moves through it. The models of soil failure are extremely complicated in agricultural soils and vary with soil and tool parameters. The dynamic soil reactions are the prime importance from the point of view of digging tool design [82]. Experiments on the rake angle of inclined tools for their performance determined that the pattern of soil failure front has a crescent shape on the soil surface with failure starting from the cutting edge of the tool and expanding into a crescent [45]. The blades up to a width of 254mm as narrow blades and stated that the draft was related to the square of velocity [83]. The analytical study of the interaction between the blades of a hoe inclined at less than 25° and the weeds in particular to the sliding of the weed along the blade edge. The conditions required for sliding and the effect on weed and blade hoe were examined [57]. A soil surface profile meter to measure soil elevations was developed above a tool surface during tillage [84, 85].

The review of all analytical and numerical models to predict soil forces acting on the tillage tools suggested the finite element analysis method as a flexible and accurate one to simulate the tillage operation. It was also suggested that these models could be applied for blades also by approximating the soil failures [63]. A new approach was developed to tool design based on the mathematical description of the tool surface with a computer program [86].

To estimate the forces acting on soil cutting implement, a good agreement between the model and experimental results at low speeds (up to 4km/h) [62, 131]. The total force per unit width can be estimated using Equ. (4.1):

$$F_s = (\gamma d^2 N_\gamma + qdN_q + cdN_c + c_a dN_{c_a}) \times w \qquad (4.1)$$

Where:

γ The = unit weight of soil, kg/m^3
C = apparent cohesion, kN/m^2,
CA = soil-interface adhesion, kN/m^2
d = depth of operation, m,
w = width of operation, m,
q = surcharge pressure on soil, kN/m^2
F'_s = soil resistance force, kN,
N_γ = soil friction cutting coefficient
N_q = soil overburden cutting coefficient
N_C = soil cohesion cutting coefficient,
In_{ca} = soil adhesion cutting coefficient

Nγ, NC, Nca, Nq are dimensionless Reece factors, which state the shape of the soil-failure surface. These factors are a function of angle of shearing resistance of soil (ϕ), angle of soil metal friction (δ), and geometry of loaded interface or rake angle (α).

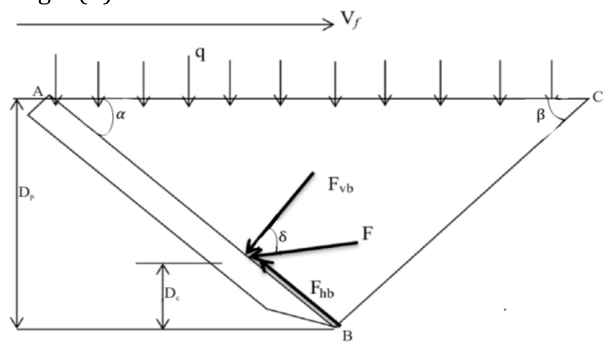


Figure 4.1. Diagram of the soil reactions acting on a blade [23]

The force (F_s) on the blade is the force required to move the tool that resolved into horizontal (F_{sh}) and vertical (F_{sv}) to the direction of motion as illustrated in Figure 4.1 and Equ. (4.2) and Equ. (4.3):

$$F_{hs} = F_s \sin(\alpha + \delta) + c_a dw \cot \alpha \qquad (4.2)$$

$$F_{vs} = F_s \cos(\alpha + \delta) + c_a dw \qquad (4.3)$$

where:

δ = Angle of friction, α = Attack/ rake angle,
P_w = power, kW, Fs = soil resistance force, kN,
S_f = operating speed, km/h

The draft is the horizontal component (F_{hs}) of soil cutting force (F_s) [131]. The soil load on the perpendicular component of soil load caused a bending moment, whereas the horizontal component induced direct stress on the blade. The force acts at the center of the resistance of the blade while the average soil resistance of the blade acts at a distance of 20% of the depth of cut measured from the cutting edge [23, 87].

Developed potato diggers and equip with vibrating blades that reduced the required drawbar pull and potato bruise [88]. Hence, soil stiffness (k) can be calculated as follows:

$$K = \frac{U \times A_c}{s} \qquad (4.4)$$

Where:

k= Soil stiffness, N/m; U =Unit draft of soil, N/cm^2;

Unit draft of soil is 12N/cm for heavy clay soil that was taken as a sample of the severest working condition during potato harvesting. Where the harvester is an oscillatory and vibratory digger, the overall parameter (T) can be calculated from the equation below, [89].

$$T = \lambda . k\,,\quad \lambda = \frac{\omega^2 A}{g} \text{ and } k = \frac{\omega^2 A}{g} \qquad (4.5)$$

Where:
λ = the ratio between vibrating and forward speeds,
ω = Angular speed, rad. /sec;
A = the amplitude of the vibration, m;
g = Gravitational acceleration, m/sec^2
k = the ratio of blade acceleration to gravitational acceleration,
V_t = Digger forward speed, m/sec.

On the other hand, a designed potato digger with a rotary blade with a required torque for rotating a blade can be calculated as below [37]:

$$Tt = T_c + T_{ft} + T_{ca} = R(F_c + F_f + F_{ca}) = R(A_c \times C + \mu N + A_{ca} \times C_a) \qquad (4.6)$$

where:
T_t = total torque (N.m), T_c = torque of cohesion force (N.m), T_{Ff}: torque of frictional force (N.m), F_c : cohesion force (N), Tca: torque of adhesion force (N.m), F_f : frictional force (N)
Fca : adhesion force (N), Ac : fracture area (m2);
C : soil cohesion (N/m2); R: blade radius (m);
μ: coefficient of friction between soil and metal;
N : normal force (N).

Shanks transferred soil resistance force on the blade to the toolbar then to the drawbar hitch system. Usually, the perpendicular component of the soil load caused direct stress, whereas the horizontal component (drawbar pull) induced bending stress on the shanks [23]. Hence, the force required to move forward is the resultant of the horizontal forces (F_{sh}) and the vertical force (F_{sv}) on the blade. Similarly, ANSYS analysis and performance evaluation of potato digger harvester revealed that the blade located on one axis at the front of the machine was with 8 arms, triangular head, leaning on the horizontal axis at three angles of 22°, 17°, and 12° as shown in figure 4.2 [90]. Determination of the horizontal inclination of the excavating shovel was subjected to force decomposition, then the force decomposes separately and perpendicular to the shovel surface hence, the relationship can be examined as below [91].

$$\begin{aligned} F\cos\theta_2 - f - mg\sin\theta_2 &= 0 \\ F_n - mg\cos\theta_2 - P\sin\theta_2 &= 0 \end{aligned} \qquad (4.7)$$

Where:
θ1 = angle between digging shovel and ground surface;
F = force required to dig the excavation of the soil, N;
M= the mass of the soil on the shovel surface, kg;
F_n = the reaction force of the shovel facing the soil, N;
f = the friction of the digging shovel against the soil; N

The friction of the digging blade calculated from the following equation:

$$f = \mu mg \qquad (4.8)$$

Where μ is the coefficient of friction surface of the blade. According to Equations of (4.7) and (4.8), we can find:

$$\theta_1 = \arctan\frac{F - \mu mg}{\mu F + mg} \qquad (4.9)$$

The length of the digging shovel was set to two parts L1 and L2 and the length L of the entire digging shovel is the sum of them *i.e.* L= L1 + L2.

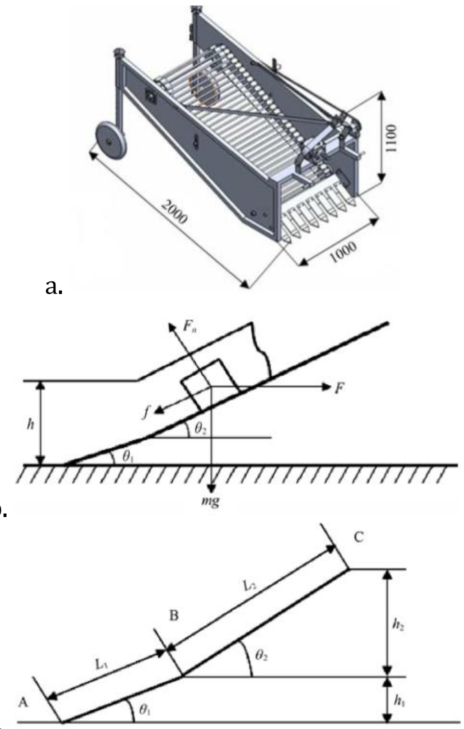


Figure 4.2. Structure of the digger blade (a), force diagram of the excavating shovel(c), and calculation length of the excavation mechanism(c) [90]

The potato can be easily transferred to the separation conveyor and satisfy the formula below [91]:

$$L = L_1 + L_2 = \frac{h_1}{\sin\theta_1} + \frac{h_2}{\sin\theta_2} \qquad (4.10)$$

Where L is the length of digging shovel; L1 is the first part of shovel length; L2 is the second part of shovel length; h1 is the first level of shovel height; h2 is the second level of shovel height.

4.2. Mechanism of Soil Tuber Separation

Soil tuber separation mechanism of potato harvesters may be oscillating, conveying, rotating, spinning, and multi-purpose principles relative to the forward linear motion of the power source. The design of the potato digger elevator machine in chain or apron chain conveyor system, the total tension loads can be summarized in Equ. (4.11) [92]:

$$T = F_s + F_i + F_g \qquad (4.11)$$

where:
T = Total chain tension, N; F_s = Upper chain tension;
Fi = Down chain tension; F_k = Lift chain tension

Similarly, each load could be computed as [92],

$$F_s = (Qt + Q_r + Q_c)gf \quad (4.12)$$

$$F_i = \frac{(Q_r + Q_c)V_e(1+f_1)}{2} \quad (4.13)$$

$$F_g = \frac{P_g}{V_e} \quad (4.14)$$

For an inclined chain conveyor, the lift chain tension required to lifting a mass at a constant speed was given in Equ. (4.15) [92]:

$$P_g = (Q_c + Q_r + Q_t)gh + \mu(Q_c + Q_r + Q_t)gl\cos\theta \quad (4.15)$$

where:
Pg = power to lift the material, W,
Pg = power to lift the material, W,
h = height of elevator, m
l= center length of elevator, m,
θ = conveyor inclination, º
f_1 = Down chain friction factor (0.10 -0.15),
Q_t = Weight of conveyed material, kg/s,
Q_c = Total chain mass, kg.s^{-1}
Q_r = Total elevator rod mass, kg.s^{-1}
f = Upper chain friction factor (0.25- 0.35),
μ = friction coefficient in elevator rod and soil-tuber mass

The maximum weight on the conveyor can be determined through the following expression [93]:

$$M = V \times \rho_{bulk} = (d \times w \times l)\rho_{bulk} \quad (4.16)$$

where;
M =Mass of the soil and tubers, kg;
V= Volume of the tuber and soil above the conveyor, m^3
d= Maximum d soil thickness, m;
w= Conveyor width, m;
ρ_{bulk} = Maximum density of the soil and potato tubers (bulk density), kg/m^3 and
l = Conveyor working length, m

The weight on the inclined conveyor can be analyzed using the inclined plane method as the conveyor slop (α), and force effects on the conveyors illustrated as shown in figure 4.3 below [93].

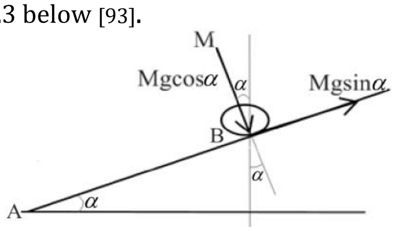


Figure 4.3. Force analysis of digging shovel (Tarek *et al.,* 2016)

The number of rollers (n_r) on the conveyor also can be computed using Equ. (4.17) [91]:

$$S = \frac{l_c}{n_r} - D_r \le D_{min} \quad (4.17)$$

where:
S = space between conveyor rods, cm,
D_r = diameter f rod, cm,
l_c = total length of conveyor chain, cm,
n_r = number of conveyors rode,
D_{min} = minimum potato tuber diameter, cm

Load due to tensions on the chain conveyor could calculate and analyze through the movement of the soil-tuber mass. Assume a point A locates at the end of the blade and at the beginning of the conveyor, which has a certain angle to the ground [94]. The velocity decomposition chart of a conveyor chain is shown in Figure 4.4 below:

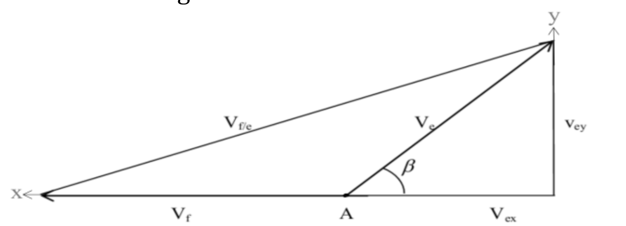


Figure 4.4. Soil-tuber velocity analysis on a conveyor [94]

Where:
A = a point of potato tuber moving to chain elevator,
V_f = machine forward velocity, m/s
V_e = resultant velocity of elevator chain, m/s
V_{ey} and V_{ex} = velocity of the elevator chain in the vertical and horizontal direction, m/s
$V_{f/e}$ = relative velocity of 2WT forward speed and elevator speed, m/s
β = the angle between the movement direction and the chain conveyor speed, (º)

An oscillatory sieve potato harvester was also consisting a connecting rod, that is a hinged member between the crankpin/tractor PTO and lower conveyor shafts or a blade, total force (F_v) applied on the connecting rod of the oscillating system could be evaluated using Equ.4.18 [95]:

$$F_v = F_s\cos\theta \pm F_i \pm m_R g \quad (4.18)$$

where:
F_v = total force acting on the connecting rod, N
F_i = Inertia force of reciprocating parts, N
F_s = net force acting to the line of stroke, N
M_R = Mass of the reciprocating parts, kg
g = acceleration due to gravity, m/s^2

4.3. Harvesting Power and Cost Requirement

The required power (P_h) expensed to harvesting a potato was estimated by the following formula [96]:

$$P_h = \frac{F_c}{3600} \times \rho_f \times \eta_{mech} \times LCV \times \eta_{th} \times \frac{427}{75} \times \frac{1}{1.36} \quad (4.19)$$

Similarly, the specific energy requirements (S_e) (kW/ha) was calculated by using the following equation [97]

$$S_e = \frac{P_h}{F_a} \quad (4.20)$$

Where:

F_C = fuel consumption, L/h;
ρ_f = density of fuel, kg/L (For diesel = 0.85);
L.C.V = calorific value of fuel (10000 kcal/kg);
427 = thermo-mechanical equivalent, J/kcal;
η_{th} = thermal efficiency of engine (≈35% for diesel);
η_{mec} = mechanical efficiency of engine (≈80%).

Costs of harvesting can be evaluated using the following equations:

$$OCM = \frac{OCT + OCM}{Fa} \qquad (4.21)$$

$$CMD = OCM + CL + MCC \qquad (4.22)$$

Where:

OCM = operational costs of mechanical digging,
OCT = Tractor hourly cost
OCM = the machine digging hourly cost,
CMD = cost of mechanical harvesting
CL = Cost of losses,
MCC = Manual collecting costs

The machine cost was also determined by using the formula below [38]:

$$C = \frac{P}{h}\left(\frac{1}{E} + \frac{I}{2} + T + R\right) + 0.9W \times S \times F + \frac{M}{144} \qquad (4.23)$$

Where:

C = Machine hourly cost, L.E. /h
P = Price of the machine, L.E.
h = Yearly working hours. ,
E = Life expectancy of the machine, year.
I = Interest rate/year.,
T = Taxes and overheads ratio, %.
R = Repairs and maintenance ratio, %.
W = Power, kW.
S = specific fuel consumption, (L/kW.h).
F = Fuel price, (L.E).
M = Operator monthly salary, (L.E).
144 = the monthly average working hours.
0.9 = Factor accounting for the ratio of rated power and lubrication.

4.4. Development of potato harvesting system

Potato harvesting requires digging of the soil along with the crop for harvesting the produce. Different harvesting systems have been developed with different harvesting mechanisms, which are discussed in detail.

4.4.1. Design and Development of Potato Digger in Ethiopia

Potato tuber harvesting takes place manually, opening furrows by a traditional plough and through a bamboo/ metal funnel attached to a traditional plough (*maresha*) in Ethiopia. Unfortunately, manual hand and animal-drawn harvesting are very laborious, tedious, slow, and high damage to the tuber pieces [98]. The existences of two types of predominant potato harvesting trends are common in Ethiopia, namely traditional plow and hand hoe. The performance of hand hoe on exposing efficiency and percentage of damage was 100 and 0.78% respectively. However, it can be characterized as a low field capacity of 0.0025 ha/h, high drudgery, and fatigue (Figure 4.5a) [8]. There were also manual harvesting practices through making holes or slits by a stick or tool and tuber collecting by hand in small areas of potato harvesting (Figure 4.5b). Manual harvesting was required at least 160man-hour/hectare [98].

Figure 4.5. Hand hoe potato harvesting tools (a) and manual potato harvesting (b)

Most potato producers in Ethiopia also used the *ard* plow (locally known as *Maresha*) to dig and lift potato tubers though whose shape and structure have remained unchanged for thousands of years (figure 4.6). Efforts made to improve the *ard* plow were based on experience, culture, and trial and error methods. As a result, the prototypes developed were found to be expensive, heavy, complicated, and did not fit into the traditional plow frames [101]. The traditional plow has field capacity, damage loss, and exposing efficiency of 0.22 ha/h, 1.06%, 89.16%, and respectively [8].

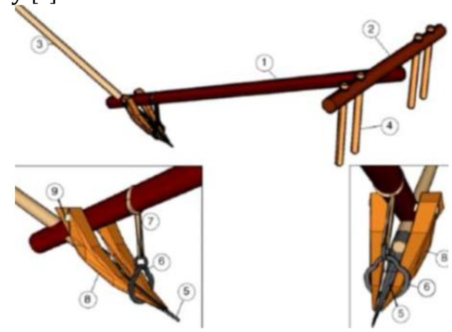


Figure 4.6. Main components of Ethiopian ard plough maresha:

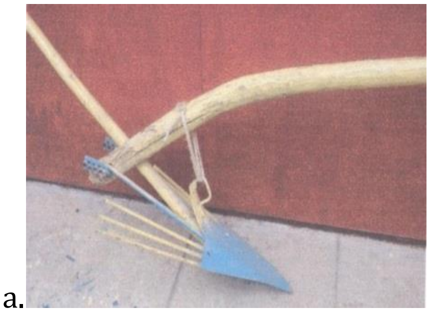
1: beam, 2: yoke, 3: handle, 4: neck holder sticks, 5: ploughshare, 6: lower metal loop, 7: leather stripe, 8: side wings, 9: wooden Pin.

The Agricultural Mechanization Research Directorate (AMRD) at Melkassa Agricultural Research Centers (MARC) modified an improved groundnut digger, to harvest potato tubers in 2001, which is an attachment to the local plow, *Maresha* (Figure (Figure 4.7a). The potato harvester was then compared with the conventional potato digging using *Maresha* plough. The two harvesting methods were compared for their technical performance concerning exposing efficiency. From the result (Table 2.1), the improved potato digger had better exposing efficiency in the first ploughing and had a cumulative exposing efficiency of 97.68% when ploughed twice. Cumulative exposing percentage with the use of the local plough, on the other hand, was 89.36% in two ploughing. This indicates ploughing once with the improved digger is almost equivalent to ploughing twice with the traditional practice. Compared to local plough, unexposed potato remained in the soil after the second ploughing was lower for the improved one [100].

No	Parameters	Treatments	
		Local *Maresha* (%)	AMRD animal-drawn potato digger (%)
1	Exposed potato during 1st ploughing	75.24	87.95
2	Exposed potato during 2nd ploughing	14.12	9.73
3	Unexposed potato	10.64	3.22

Table 1. Performance of conventional and AMRD animal-drawn potato digger

The redesigned and improved version of the AMRD digger was also found that an exposure efficiency, damage loss, and field capacity of 90.069%, 1.03%, and 0.217 ha/h respectively [8]. On the other hand, based on testing and performance evaluation of the AMRD digger, the improved design of the Bahir Dar digger (BD) had been developed by the Bahir Dar agricultural mechanization and food science research center in collaboration with the universities of Bahir Dar and Addis Ababa. BD digger is animal-drawn with a smooth or rounded lifter edge with exposure efficiency, damage loss, and field capacity of 92.906%, 0.81%, and 0.247 ha/h respectively. An increase in the rake angle of the digging shear increased the depth of penetration of the lifter by 2.40cm when the damage was decreased by 3-5% and the exposing efficiency increased by 2-3% compared to the AMRD potato digger [8]. Another improvement in potato digger design is the *Selam* potato lifter improved by *Selam* Vocational Training Centers in the private sector, which the prototype implements was based on Latin American design. The lifter has depth control mechanisms, good exposing capacity, and having an increased angle of sheer than the rest of the tuber harvesting tools (Figure 4.7b)[99].

a.


b.


Figure 4.7. Melkassa digger (a) and *Selam* potato lifter (b)

The other developed machine was a single axle tractor operated potato digger elevator which was designed, constructed, and evaluated in EIAR/MARC (Figure 4.8). The developed prototype potato digger elevator was drawn by a 15hp power tiller/single axle tractor. The study indicated that the optimum combination of rake angle and elevator slope was 15° and 20°, respectively. At this optimum condition, damage percentage, conveyance efficiency, cleaning efficiency, drawbar pull, fuel consumption, wheel slip, soil swelling factor, soil mean weight diameter, pulverization ratio, and field capacity were 3.39%, 89.64%, 91.87%, 2959.1N,14.87 l/ha, 17.67%, 20.25%, 17.44 mm, 78.09% and 0.127 ha/h respectively. Hence, the prototype machine is acceptable with a prospect of modification and adoption for small and medium-scale farmers [94].

a.

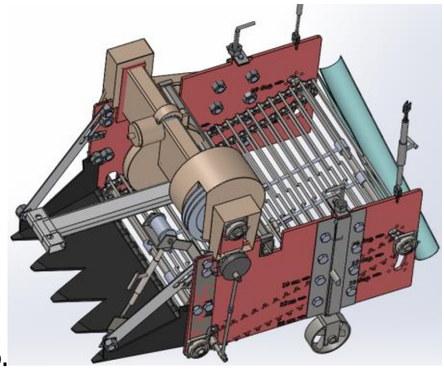

b. 

Figure 4.8. Single axle tractor operated potato digger elevator (a), and an isometric view of a machine (b)

4.4.2. Types of Potato Harvester

Root crop harvesting, machines/equipment can be classified in several ways. Generally, classified based on the source of power-operated that may be manual operated (hand tools and digging aids such as spade, digging and picking fork, etc.), animal-drawn equipment (country plow, animal-drawn digger, etc.), tractor operated equipment (spinner-digger, elevator-digger, digger-shaker-windrower, etc.) and self-propelled machine (potato combine harvester, etc.). Root crop harvesting machines/equipment also divided into the mode of hitching, which is attached to a tractor or power source in case of trailed, mounted, semi-mounted and self-propelled form. The other way of classification was the unit of operations it performs. Thus, include simple multipurpose digger, digger-shaker, digger-elevator-windrower, digger-shaker-conveyor, and digger-shaker-windrower [101].

Based on the completion of the operation, root crop harvesting equipment may be direct harvesting equipment (accomplishes the complete operation of digging and separating in one go) or indirect harvesting equipment, (it accomplished complete operations in more than one passes) [102]. Root crop harvesting can be also divided into bulk root crop harvesting and controlled root crop harvesting. The bulk root crop harvesting was digging the soil and the crop, while the system control depends on harvesting only the crop. Complex harvesting machines include spinners and elevator diggers. A spinner digger is working effectively in light soil, but may not be suitable for use in heavy sticky soil [103].

4.4.2.1. Manual harvesting

Harvesting is the complete recovery of potato tubers out of ridge and separating them from the bulk of soil, roots stones, and haulms. Various traditional harvesting practices have been attained in different countries. One of the simplest designs for potato harvesting is the hand tools and plough resembling a ridging body with its moldboards replaced by rods or slats. While it is certainly very gentle in its treatment of the potatoes, the plough does not expose the tubers efficiently for convenient picking up [104]. Potato harvesting in Ethiopia was usually done manually and using animal-drawn *maresha* but it is drudgery and time-consuming [11]. Hand hoe harvesting should not be used because due to more damaged tubers, takes a lot of time, and low to expose. A better tool to use, if other options are too costly is the garden fork which is best for spot harvesting and causes less damage to tubers than the hand hoe (Figure 4.5) [14]. This approach should only be used initially for sections with high bacterial wilt incidence to avoid mixing potentially diseased potato with healthy potato at the end of the harvesting operation. Most developing countries are harvested by hand. Usually, roots and tubers grow beneath the soil are likely to a mechanical injury at harvest because of digging tools, that is wooden sticks, machetes (or cutlasses, pangas, or bolos), hoes, or forks [2].

Egyptian farmers have almost smallholdings and the manual method of hand hoe for harvesting potato is widespread despite it needs a lot of labor, cost, and time, on the other side; the large harvesting machines are uneconomical in those small areas [38]. Potato harvesting in India was also largely done by using age-old manually operated hand tools with a few animals drawn implements. The traditional method of harvesting requires about 160 man-hour/ hectare [10]. Manual potato harvesting requires more energy (600 man-ha/h) than with an animal-drawn potato digger (400-425 man-ha/h) [107]. Other reports exceed the manual harvesting of potatoes about 800 man-h/ha, which is how it was quite a labor-intensive job. The introduction of the potato, haulm killing by hand sickles required 20 to 25 man-h/ha [108]. Labor requirements for picking tubers digging manually with a spade or hand hoe were 403 man-h/ha [109]. In other cases, 600man-hr./ha were required for manual digging and harvesting of potato [110]. Similarly, labor requirements under the traditional method of potato harvesting can be as high as 22 - 62 man-days per hectare [2]. The field also becomes undulated when a potato is harvested manually and requires 2-3 plowing for the next crop that exceeds the cost of production of the potato due to labor charges. It requires more energy (600man-ha/hr.) than with an animal-drawn potato digger (400-425man-ha/hr.) [107].

4.4.2.2. Potato harvesting using the animal-drawn digger

An animal-drawn digger is an alternative harvester than a manual harvester; drawn by a single or pairs of animals with a man as an operator. It is different in design and features that are discussed below in detail. An animal-drawn single-row potato digger, with a V-shaped share, was designed and saved labor and reduced the cost by 94.0% and 60.5% respectively (Figure 4.9b). The improved animal-drawn potato digger has an adjustable system with the size of the animal [111, 112]. An ox-drawn potato lifter was also designed by the National Agricultural Research Organization of Indian (NARO) based on the groundnut digger and the ordinary ox-plow with a moldboard replaced by a pronged fork. For operation, the pair of bullocks pull the implement; the flat piece attached to the share tip penetrates in the soil and harvested crops along with the soil lumps slide over the moldboard (Figure 4.9a) [105].


a.


b.

Figure 4.9. NARO potato lifter (a), improved digger (b)

Indian Punjab Agricultural University developed an animal-drawn single-row potato digger, which is suitable for digging and exposing tubers in a row. It is provided with a V-shaped blade with round bars at the rear (Figure 4.10a) [113]. The ICPR designed an animal-drawn single-row implement suitable for digging out potato tubers and groundnut vines. It saved 94% labor and operating time and 60.5% on the cost of operation compared to the conventional methods of digging with spade and hand pulling (Figure 4.11b). Animal-drawn potato diggers require 400-425 man-ha/hr. [107].


A.


B.

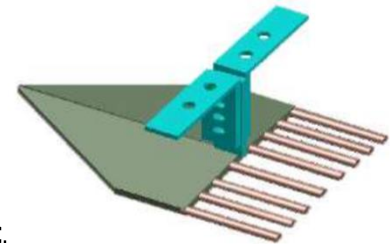
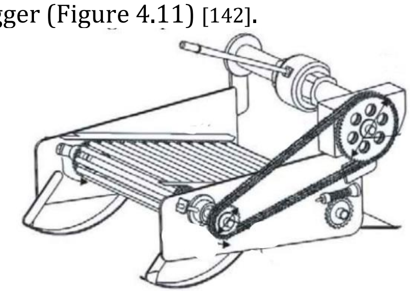

C.

Figure 4.10. V-shaped potato digger (a) animal-drawn potato digger (b) and animal-drawn improved digger(c)

A lightweight, single row animal-drawn improved digger was developed and evaluated for harvesting tubers (Figure 5c) [114]. The Digging efficiency and field efficiencies were 93% and 88% respectively.

4.4.2.3. Potato harvesting using a tractor-drawn digger

Both single and double axel tractor-drawn diggers are available in a variation of working mechanisms. Power tiller-operated potato digger can operate a row at a time. Field evaluation indicated that field capacity and field efficiency was 0.12ha/h and 75% respectively. The machine was efficient such that the tires run along the furrow to avoid compression damage to the tubers. It was much faster, more efficient, and less damaged tubers compared to an animal-drawn digger (Figure 4.11) [142].


a.

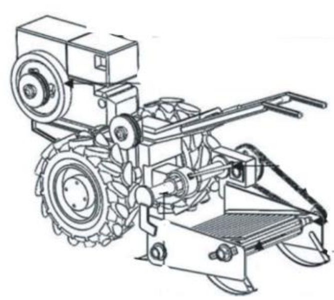

b.

Figure 4.11. Power tiller operated potato digger (a) and potato digger attached to power tiller (b)

The major advantage of a potato harvesting machine with a chain conveyor is delivering potatoes on a row in the field that facilitates the gathering of tubers by hand. Compared to other types of harvesting machines, this type of machine is causing soil erosion and is not used when the soil is moist and sticky [115]. In the Netherlands, a lightweight potato lifter was developed based on a round ridge cutter and a helix-shaped sorter results showed that the damage to tubers was low, cleaning was very easy and soil compaction was minimal [116]. Also, a new potato digger was developed powered by a power tiller. The average field capacity of the machine was found to be 0.139ha/h with 80.90% field efficiency [117]. A potato digger with an oscillating blade was evaluated on the adaptability of an oscillating tool to a root harvesting machine which gave a reduction in the draft and better soil break-up. The oscillatory blade reduced the draft up to 76% and increased the soil separation up to 96% [118].

A design and evaluation of a vertical lift digger for harvesting potatoes. The harvester is a three-point hitch mounted with telescoping wheels for setting and controlling the digging depth. The digger bed and weighted anti-roll belt are driven by a hydraulic motor powered from the remote hydraulic system on the tractor. The weight belt was driven at the same speed as the digger bed to prevent relative motions between the surfaces and skinning of the potatoes. Clod rollers were used after the main bed to increase sieving and provide a horizontal surface [119]. A tractor-operated oscillating type potato digger is a two-row potato digger with a horizontal oscillating motion that gives high work output, better tuber exposure with almost negligible bruising to tubers. The potato digger with a horizontal oscillating motion has a continuous triangular cutting blade in its digging unit [112]. It can be concluded that the vibrating blade equipped with a potato harvester was found to have a lower draft in the tests than other commercial harvesters [141].

A small size one-row four-wheel tractor-drawn reciprocating prototype machine for digging potato was carried out to evaluate the performance of the machine under four forward speeds of 1.40, 2.30, 2.95, and 3.50km/h, three-blade rake angles of 10°,14°, and 20°, and three digging depths of 25, 30, and 35cm. The results revealed that the proper operating conditions for the prototype potato digger are forward speed of 2.30 km/h, the rake angle of 14°, and digging depth of 30cm to achieve a field capacity of 0.23fed/h and the lowest percentage of total losses and costs with high harvesting efficiency [38]. Tractor-drawn potato digger elevator is commonly used and has field capacity, field efficiency, and exposes efficiency were 0.2-0.3ha/h, 60-70%, and 100% respectively (Figure 4.12) [111].

a.

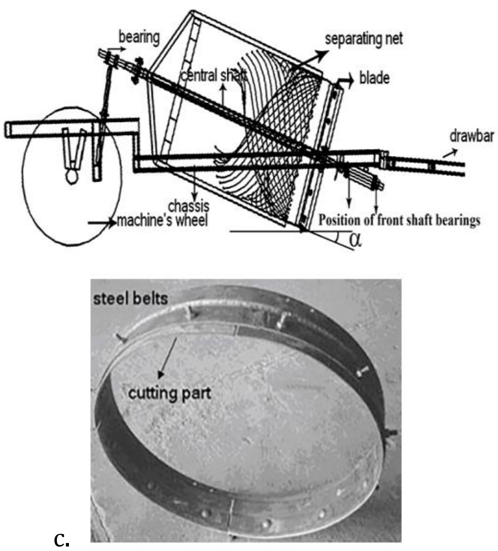

b.


Figure 4.12. Different types of potato digger elevator (a, b, and c)

The potato digger cum elevator is the most acceptable digging device among potato growers. It gives high work output, better tuber exposure. The unit comprises a digging blade, a rod chain conveyor, a gearbox, gauge wheels, and a frame. The machine digs two ridges of the crop at a time and picks up the soil potato mass by a rod chain conveyor [112]. Spinners are also a potato slasher operated by power take-off from the tractor on which attached and moves forward, a digging share runs beneath the row of potatoes, loosening them and the soil encompassing them. Following the loosening process, rotating forks, or tines, strike the row at right angles (Figure 4.14a) [10]. On the other hand, potato diggers were with a rotary blade connected by a drawbar on the arms of the tractor during work; the blade is circular and formed from two parts of cutting and preserver (Figure 4.14b). The separating net cut soil after the blade path arrives in the separating net; at this part, the soil should be separated from potato tubers. The average of damaged potatoes was got 4%. The blade slope cannot be more than 15°. The problem of penetration in soil was observed at slopes less than 10° [2].

a.


b.



c.

Figure 4.13. Spinner potato harvester (a), rotary potato digger (b), and rotary potato digger blades (c)

A tractor-drawn trailed type two-row potato digger windrower was developed essentially a double chain elevator digger with additional rollers, a trash separating system, and an adjustable V-shaped scraper. During the field operation, the rollers were pressed upon two adjacent ridges to make them loose and friable. These are then lifted by digging blades and passed on to the vibrating primary and secondary elevator conveyors. While the bulk of the soil gets shifted through those conveyors the tubers along with trash fall upon an inclined belt conveyor. The trash gets separated and the tubers roll down to get windrowed in a shallow channel made by the V-scraper during the evaluation on the field condition [120]. A multipurpose digger was design, developed, and field tested, in which the blade enters the ridge below the potato zone and cuts the ridge slice from the main soil mass. The slice with tubers comes over the ridge-opening device that opens the whole mass in such a way that tubers are rolled and exposed. There was little effect of speed variation on tuber damage in dry field conditions, field capacity reduced by 0.13, and 0.02ha in a multipurpose and elevator digger respectively [121]. A single hill digger was developed capable of digging hills of potatoes spaced 750 mm apart and depositing them on the soil without mixing tubers from adjacent hills. The use of the digger improved the effectiveness and efficiency of the harvest crew. The potatoes are cleanly separated from the soil and individual plants remain well separated which makes it easier to do their job [122].

A potato digger was developed by adding a vibrating device to operate the digging blades and reduce the required drawbar pull and potato tuber bruising and showed that the drawbar pull of the developed digger was decreased by 25.17, 25.91, 28.43, and 30.47% at forwarding speeds of 0.9, 1.5, 1.9, and 3.2 km/h, respectively compared with the original digger records at the amplitude of 10 mm frequency of 1200 rpm [90]. An oscillating type potato digger was developed and incorporated the horizontal oscillating motion. The optimum speed of operation of the digger was 2.0-3.0 km/h [120]. An improved prototype of a tractor-drawn was designed oscillating potato digger and the main emphasis was given to vibration control in the design. As the forward speed increased from 0.35 to 0.75 m/s, the damage to tubers increased from 0.3 to 0.7% and the undug tubers increased from 6.6 to 14.4% [123].

Generally, potato harvesting through either manual or animal and tractor-drawn diggers have different levels of drudgery about 600 man-h/ha for manual digging as against an animal-drawn plough which reduced the labor to about 300 man-h/ha, and a tractor operated digger required 80-90man-h/ha[71]. A two-row vibrating blade potato digger was designed and was increased travel speed, decreased shatter bruise, and a black spot of potatoes due to more retention of soil on the blade; that draft force decreased as vibrational frequency increased and travel speed decreased. The draft varied from 7.9 to 12.2 kN and the average draft/unit area of furrow slice was 3.3 to 4.2 N/cm^2 for 1.7 to 3.3 km/h forward speed [124].

4.4.2.4. Potato combine harvester

Potato combines can be dividing into a tractor-operated potato combine harvester and a self-propelled potato combine harvester. Tractor operated potato combine was an offset trailed type tractor operated and single row, having integrated 2 ton capacity of the container (Figure 4.15) [111]. Otherwise, self-propelled harvesters(Dewulf R3060) with a bunker is recommended as the best option for harvesting potatoes for large and medium-sized production with cultivation in loamy soil, providing an annual economic effect as a result of reducing operating costs [143].

a.

b.

Figure 4.14. The tractor was drawn potato combine harvester (a) and potato combine loading system (b)

On the other hand, potato combine harvesters divided into straight thru and the windrower harvester. The straight-thru is the more efficient potato harvester, especially in sandy soils. It is a self-propelled harvester and harvests up to 6 rows at a time and a 4-wheel drive with a higher hp engine. It was reduced the time of harvest because it doesn't involve the extra step than a windrower harvester that causing less damage to the potatoes when harvesting. It is hydraulically driven and controlled by the cab. The straight thru harvester is self-propelled so it doesn't need to be tractor-drawn which saves fuel. The straight thru harvester has an automatic shut-off system which causes the engine to shut down immediately after the job is done. It has a high life expectancy (figure 4.15).

a.
b.

Figure 4.15. Straight thru potato combine harvester under operation (a and b)

Windrowers are simplified harvester that travels before the main harvesting. The windrower digs the potatoes and puts them in between intact rows. The windrowers can be self-propelled or tractor drawn. It is efficient for sandy soil having folding vine cutter. The tractor-drawn windrower was a 1000 rpm PTO operated, rear leveling, and rear steering. Windrowers have adjustable digger blades and digger beds lift with right or left-hand discharge. It can be hydraulically controlled from the cab and harvests up to 6 rows at a time and 300hp tractor operated (figure 4.16).

a.
b.

Figure 4.16. Windrower potato harvester (a) and Windrower harvester under operation (b)

Besides, now a day complex machines that can integrate potato haulm removing, harvesting, cleaning, and sorting mechanisms in a single pass have been invented in the potato community. A machine with a bulk harvesting system through unearthing relatively large volumes of soil that contain the roots to be harvested had been introduced. The primary function of the machine is to sort the potatoes from the soil, soil clods, and stones as gently and completely as possible. The actual process volume in this two-row machine as shown in figure 4.18 is defined by the horizontal shear plates (2) and the vertical shearing coulters (1 and 3). Machine elements are designed to elevate (4) the clean potatoes into storage (figure 4.17) [125].

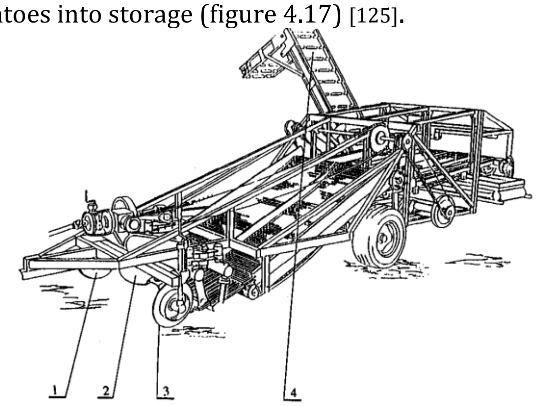


Figure 4.17. Potato combines harvester

To improve the process of separation of a heap of root crops, namely to reduce the degree of their damage at the satisfactory separation of soil impurities and crop residues, a new system of cleaning has been suggested, as shown in Fig. 4.18. For performing this system of root crop cleaning, the consecutive arrangement of the operating elements has been suggested: digging element 1, active shaking rod conveyer 2, beater shafts 3, and cleaning rolls 4 [14].

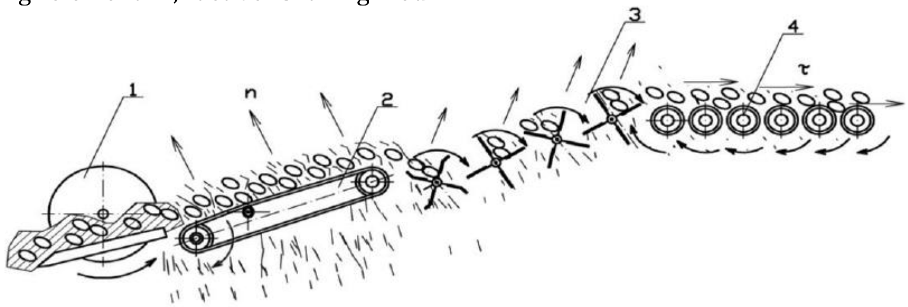


Figure 4.18. Root crop and potato cleaning system [40]

The integrated potato harvesting machine with heap separation function was introduced as shown in figure 4.19. The separation of soil and the removal of crop residues is done by an intake conveyor (6). As this takes place, a heap moves up to a receiving roll (8) and a transmission L-shaped conveyor. Rods (9), which are hinge-mounted to a frame, are pressed to the canvas of an intake conveyor by their running ends and are used for removing the heap of crop residues. A receiving roll (8) (a hollow shaft), which turns towards the canvas of an intake conveyor, has several functions: it helps to tear tops off roots and to clean the rods (9); it shakes, turns over, and presses heap components to the canvas of an intake conveyor and drops the soil, clods, stones, and tops on the field; it reduces the impact force of roots and the canvas of a conveyor [14].

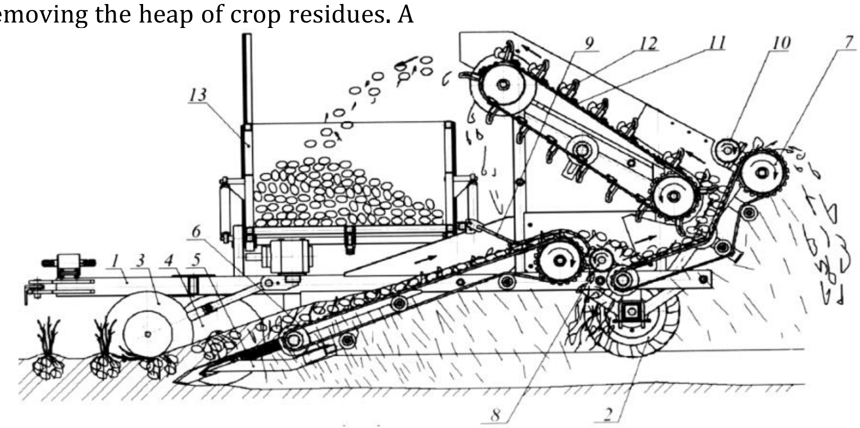


Figure 4.19. Design and process flow sheet of a potato harvesting machine (14)

1: a frame; 2: running wheels; 3: track roller; 4: cut off disk; 5: shares; 6: intake conveyor; 7: transmission L-shaped conveyor; 8: receiving roll; 9: top separator rods; 10: beater roll; 11: loader conveyor; 12: scrapers; 13: hopper

5. Performance Evaluation of Potato Harvesters

Several animal-drawn, tractor-mounted equipment and potato combine harvester have been developed for potato lifting or harvesting operations. Literature indicated that performance evaluations of potato harvesting systems have been conducted between those different harvesting systems. Tractor-drawn potato digger cum elevator was evaluated with a manual digger that capable of digging potatoes with a minimum injury, working on the principle of digging and elevating the soil and potatoes simultaneously. The tractor has drawn a potato digger elevator that is suitable for digging and exposing tubers. It saves 75% labor for operating and 50% cost of operation compared to the conventional methods of manual digging with spades or by cultivators. It also resulted in a 4-5% reduction in harvesting losses [107].

A comparative field performance study on Manual Harvesting (MH), Multipurpose Digger (MPD), and Elevator Digger (ED) were done. He revealed that the average percentage of tuber damage in MPD was low because tubers rarely meet the metal surface. In ED, a lot of surface contact is there as tubers travel on the metallic web before falling compared to MPD. This may be due to less clod formation resulting from high-speed impact in MPD. The labor requirement for picking was less by 36.0%, compared with that of MH. Pulling of haulms and lifting of tubers became easier in digging by MPD. Tuber damage was also reduced by 72% [121]. The velocity ratio (the ratio between oscillation speed and forward speed of travel) of 1.38 was the optimum condition for the performance of an oscillating digger [46]. The velocity ratio (α') also can be defined as:

$$\alpha' = \frac{2Ln}{V_f} \quad (5.1)$$

Where,

L=length of sieve stroke, m
n=Revolution of the eccentric wheel, rev/s
V_f=Forward speed of travel, m/s

The parameters for the performance evaluation of potato harvesters are exposing capacity, damage index, conveyance efficiency, cleaning efficiency, wheel slip, soil mean weight diameter, pulverization ratio, soil swelling factor, fuel consumption, draft requirement, field capacity, etc. that may vary depending on the type of the potato harvesting machine [2, 97]. To evaluate the digging (exposing) capacity of the potato harvester, hand digging using a hoe can be done over a depth deeper than the harvester digging operation of the machine in a sample. A machine exposing efficiency (η_p) can be examined using the formula below [128]:

$$\eta_p = \frac{M_L}{M_L + M_{UL}} \times 100 \quad (5.2)$$

where:
M_L = Mass of lifted root crop over the soil surface, kg;
M_{UL} = Mass of un-lifted root crop, kg

The percentage of damage also can be assessed by taking a sample of tubers randomly after harvesting from the test plot by weighing and taking into consideration the mass of tuber (kg), which has no bruise or cut for each of the samples and the mass of damaged tuber (only serious damaged and neglected slight damage). Through collecting and weighing all visible tubers, the damaged tubers were separated, measured (serious damaged and avoid slight damage), and undamaged potato tubers after harvesting and recorded as a percentage. The percent could be determined using the following formula [128]:

$$\eta_d = \frac{M_D}{M_{ND} + M_D} \times 100 \quad (5.3)$$

where:
M_D = Mass of seriously damaged root crop, kg,
M_{ND} = Mass of tuber exposed and not damaged, kg.

On the other hand, the damage index can be estimated by taking a sample of tubers and separating them into undamaged, by scuffed, peeled, and severe classes. Though compute the percentage of each class to the total weight of a sample then multiplied by their appropriate factor [93]. Hence, the percentages are multiplied by the following factors:

$$Damage\ index = 1scuffed \times 1peeler \times 3severed \times 7 \quad (5.4)$$

Conveyance efficiency of conveying process can be estimated to know how efficiently conveying unit pick the tubers, especially for elevator diggers. It was defined as follows [9]:

$$\eta_v = \frac{M_h}{M_L} \times 100 \quad (5.5)$$

where:
M_h = Mass of tubers picked by conveying unit, kg,
M_L = Total mass of tubers dig, kg

Similarly, cleaning efficiency could be computed by taking a sample and measured the potato tubers and other impurities including soil clod through collecting at the outlet of a machine in case of vibratory and elevator digger. Then, cleaning efficiency is a ratio weight of tuber to the sum of tuber and impurities expressed in %. The cleaning efficiency of a machine was expressed as:

$$\eta_v = \frac{M_h}{Ms} \times 100 \quad (5.6)$$

where:
M_h = Mass of tubers picked by conveying unit, kg;
M_S = Mass of clod-tuber mix dig and picked kg

The other parameter was the soil swelling factor, which is a percentage increase in disturbed and lifted soil volume over the original value during the potato harvesting operation. It can be examined by taking soil samples using a soil sampler before and after harvesting. Then soil structural alteration was the change in average soil volume and density through measuring balance [129]. The swell factor was computed in Equ. (5.7):

$$SF = \frac{\gamma_O - \gamma_f}{\gamma_f} = \frac{V_f}{V_o} - 1 \quad (5.7)$$

where:
γ_f = the soil density after cutting, kg/m^3;
γ_o = the original soil density /before cutting, kg/m
V_f and V_o = the soil volume after and before cutting, m^3

Soil aggregate size distribution is the temporary estimation of surface soil aggregate-size distribution to evaluate soil clod size and level of soil pulverization to separate soil tuber through potato harvesters and tillage implements. Soil aggregation is expressed by soil mean weight diameter (SMWD) and soil pulverization ratio [23]. The pulverization level of the soil clod size between the soil, grades are determined by the soil sample left on each soil sieve on the harvester. Soil aggregate size distribution of soil can be determined using Equ. (5.8)[34]:

$$Gs = \frac{M_r}{M_t} \quad (5.8)$$

where:
Gs = grain size distribution; M_r= mass of retained, kg; M_t=total mass of soil, kg

Mean weight diameter was also determined through the standard dry-sieving method [33]. Hence,

$$SMWD(mm) = \frac{\sum W_i X_i}{\sum W_i} \quad (5.9)$$

where:

MWD = soil mean weight diameter, mm
X_i = mean diameter of any size range i of any aggregate, mm
W_i = weight of aggregate in size range i as a fraction of total dry weight, g

Soil pulverization ratio is also the percentage of the soil weight fraction composed of soil clods less than or equal to 25mm, which passes from the sieve mesh of 25mm to the total weight of clods produced by the potato digger [130]. It was known that the minimum arithmetic tuber diameter was around 30mm [137]. On the other side, the fuel consumption of a tractor-drawn potato harvester can determine through, the fuel tank filled up to the neck of the fuel tank before and after the harvesting operation. The amount of refilling measured after the harvesting was the fuel consumption for digging operation and it was expressed as litter per hectare. The amount of fuel used to refill the fuel tank was illustrated as [131]:

$$f_c = \frac{C_r}{A} \quad (5.10)$$

where:

F_c = fuel consumption rate, l/ha,
C_r = reading of cylinder, l,A = area, ha

Similarly, wheel slip of tractor-drawn potato harvester can measure through the base (unloaded) distance for a given number of drive wheel revolutions and then measuring the loaded distance for the same number of wheel revolutions [131]. The relation gives:

$$S\% = \frac{B - L}{B} \quad (5.11)$$

Where: B = base distance, L = loaded distance

The total drive-wheel revolution under load/harvesting (R) and no-load (r) should record during a testing slip. Then,

$$S\% = \frac{R - r}{R} \times 100$$

The theoretical field capacity is also the result of work speed multiplied by the width of the working area. The effective field capacity could be the theoretical value multiplied by the field efficiency. The effective field capacity of the machine can be calculated as shown below [132]:

$$EFC = \frac{A}{T_p + T_1} \quad (5.12)$$

where:

EFC = Effective field capacity, ha/h,
A = Area covered, ha; T_p = Productive time, h,
T_1 = Non-productive time, h

Field efficiency can be estimated as shown below [132]:

$$Ef = \frac{EFC}{Ct} \times 100 \quad (5.13)$$

where:

Ef = Field efficiency, %,
EFC = Effective field capacity, ha/h,
Ct = Theoretical field capacity, ha/h.

The draft requirement of a potato harvester is the basic parameter that could be measured using a drawbar dynamometer attached to the machine and the power sources/two tractors and a dynamometer between them. The first tractor was power sources while the second was towed and served as a machine/digger carrier. Similarly, the economic evaluation of the potato harvester machine could be analyzed in terms of economic aspects including fixed cost, the variable cost, the breakeven point (BEP), benefit-cost ratio (BCR), and payback period (PBP) [9, 23, 133]. The total cost of the carrot digger was determined based on fixed and variable costs. The cost of operation obtained was compared with the conventional practice of digging.

6. Harvesting Losses

Mechanical damage loss in agricultural products shows variation depending on the physical and biological property and structure of the product and the nature of the external forces on the product. Agricultural materials are exposed to initial mechanical damages during planting, harvesting, threshing, handling, storage, and transportation. Generally, the damage is incurred as a rupture or breakage due to collisions and excess deformation by agricultural machines [134, 135]. There are four major types of potato bruise damage: skinning, black spot bruise, shatter bruise, and pressure bruise. The first three result from the potato hitting objects, such as equipment, clods, rocks, or other tubers during harvesting and handling operations. Skinning or feathering often results from handling immature potato tubers, resulting in the skin being scuffed and rubbed off. Shatter bruise results when impacts cause cracks or split in the potato tuber skin. The cracks may extend into the underlying tissue. Diseases such as Fusarium dry rot, early blight, and bacterial soft rot easily invade tubers that have shatter bruises. Pressure bruise develops in storage, causing a flattened or depressed area on a potato tuber [136].

To reduce physical damage, regular monitoring is recommended as tubers move through the different steps along with the harvesting, washing, and grading equipment. Potato harvesters have been modified to prevent damage to potato crops (through altering the chain speed, riddle chain amplitude, or blade tilt angle and digging depth) [137]. Several factors affect susceptibility to bruising during harvest. The physical condition of the soil such as type is important, but the key controllable factor is soil moisture. For the minimum risk of bruising, soil moisture at harvest should be between 60 and 80% of field capacity (FC). The most influencing bruising factor during harvesting also hydrated tubers (turgid), tuber temperature, soil moisture, harvesting, and piling operations. Break in the skin allows tubers to lose water or dehydrate, and entry of pathogens into the tuber causing storage rots [138]. Potato harvesting is one of the most important operations that have to be performed preciously to have good potato production. It has a direct effect on potato bruising. Bruising has an essential effect on potato marketing. Farmers avoid this damage by fitting the tractor with narrow tires but this remedy has a side effect as it requires higher horsepower and causes a higher slip percentage. For this reason, during harvesting, farmers fit narrow tires to the tractor's axles to avoid crushing the tubers before harvesting and move safely between rows. Although this kind of tire is very helpful to bruising it decreases tractors drawbar pull [88].

Diseases such as Fusarium dry rot, early blight, and bacterial soft rot easily invade tubers that have shatter bruises. To prevention at bruise harvest integrated approach is required to maximize the percentage of bruise-free potatoes. This involves harvesting under as nearly ideal temperature and soil moisture conditions as possible, along with matching the volume of material flowing through the harvester to its capacity. The speed of conveyors on the harvester may need adjusting to keep a full volume of material flowing through the harvester [139]. After the skin of tubers has become stronger it is then possible to dig out tubers using appropriate tools or manually not to damage tubers during harvesting. Tubers should be cleaned and free from soil other inert materials immediately after harvesting. Then afterward it will be important to separate the tubers for seed purposes and other purposes. It should be kept safely in appropriate areas not exposed to insect pest attacks [4].

The use of an orbitally vibrating digging blade reduced potato damage below the levels normally encountered in conventional potato diggers. Harvesting practices largely determine the extent of the damage. Too wet soil (especially clay soils) tends to stick to tubers which hamper the washing process and increases the soil load in the washing water while too dry soil can form clots that hamper harvesting and leads to mechanical damage to tubers. A light irrigation 2 to 3 days before harvesting, can address this problem. It should ensure that the harvester is correctly adjusted [68]. The blade must be set deep enough so that the roots beneath the tubers are cut off. The ground speed of the harvester must be in pace with the chain speed to ensure that the tubers run on a bed of soil over the chain bars [140]. However, too much soil should not move with the tubers over the bars as stones and gravel damage the tubers. Where tubers are harvested by hand, the risk of mechanical damage is lower compared to when tubers are lifted with automatic harvesters. Workers must not walk or sit on a load of potatoes on its way to the packhouse because the tubers can be bruised which is not conspicuous and as a result, these tubers are not removed during sorting. Internal bruising makes these tubers susceptible to rotting organisms. The findings confirmed that a high proportion of tubers are left unharvested in the ground (38%) or are damaged during harvesting (e.g., 19% of harvested tubers when using hand hoes). This calls for an urgent need to develop more effective harvesting equipment [105].

Narrow walled tires on tractors and harvesters should be used during harvest, and uniform spacing must be maintained to reduce lateral pressure on the hill to prevent damage to tubers that are set high in the hill. The rolling of vines can increase the chances of tuber damage, especially in fields with more rocks and stones. Hence, black spot is a widespread type of impact damage in potato tubers caused by mechanical stress during harvest and handling. Black spot bruise is difficult to detect in intact tubers without peeling as the skin is not damaged [141]. Harvester's evaluations have shown that the most important factor influencing bruising is the ratio of ground speed to conveyor speed. Adjust the ratio of the individual conveyors to each other and the forward speed by changing the conveyor sprockets. The use of windrowers to increase the flow of material into the harvester can also reduce bruise damage by increasing the volume of tubers on the primary and subsequent conveyors. The potato tubers should be carried up the draper chains at nearly the same speed as, or slightly faster (5-10%) than, the machine moves forward. If the conveyors move too slowly, the tubers bunch up, causing mechanical problems and increasing damage due to bumping against each other. If the conveyors move too fast, the tubers also move rapidly. This means that when they hit another tuber or a part of the machine, there is a higher probability of more damage [73].

7. Conclusion

Crop production, specifically potato harvesting is chronological and critical work to be performed in time. If harvesting is delayed, or fast it increased the chance of disease infection, tuber rotten, and short storage life. Different works of the literature revealed that average potato field soil moisture content and tubers-soil temperature should be 10-15% (*db.*) and 45- 65^{o}F respectively.

Design factors for potato harvesters were physical and mechanical properties of potato tuber, soil parameters, and machine-based factors. The machine parameters, influencing the performance of the root crop harvester were the design condition of the machine-related to forward speed, rake angle, blade geometry, operating depth, conveyor oscillation amplitude, conveyor frequency, conveyor speed, and conveyor slope. Determinations of these factors are needed in the designing and selection of agricultural machines. Hence, it can be generalized as;

- Optimum values for significant and consistent in tubers lifting percentage was conveyor inclination of 10-20° for chain conveyor type potato diggers.
- The minimum draft, maximum pulverization of soil, and high harvesting performance the rake angle of recommended being 15-25°.
- The recommended field speed of potato harvesting machines also could be 2.5-6.5km/h.
- Vibratory potato digger's best performance was at vibration amplitudes and frequencies of 10-20cm, 4.5-8 Hz, respectively.
- Besides, the potato harvester for a high percentage of lifting tubers with low damage, the optimum-digging depth could be 12cm to 22cm.
- The best blade shape for the minimum draft and maximum recovery of potato lifting share are convex, V-scoop, and triangular fork type is recommended and
- The ratio of ground speed to conveyor chain speed to be 1-1.50 to smooth out the flow of tubers through the harvester and reduce tuber damage.

All designs and improvements made on the potato digging machines can be concluded on reciprocating, conveying, rotating, spinning, and multi-purpose operating principles relative to the forward linear motion of the power source. So that, any potato digging can be grouped into rotor conveying potato harvester, rotary blade potato harvester, reciprocating/vibrating digger, multipurpose digger, and spinners/slashing potato digger. Based on power sources, it can be manual, animal-drawn, tractor-drawn, and self-propelled combine harvesters.

Also, there are potato combines that were dividing into tractor-operated and self-propelled potato combine harvesters. Potato combine harvester may also divide into straight thru and the windrower harvester. The windrowers can be self-propelled or tractor drawn.

8. References

[1] Food and Agricultural Organization (FAO). 2009. Sustainable potato production- Guidelines for Developing Countries. Agricultural and Forest Meteorology,127. https://doi.org/10.1016/j.agrformet.2004.08.003.

[2] Younus, A.E. and Jayan, P.R. 2016. Performance evaluation of root crop harvesters. International Journal of Engineering Research and Development. 11(06):38-52.

[3] CSA (Central Statistical Agency). 2012. Population size by Age, Area, and Density by Region, Zone, and District. Addis Ababa, Ethiopia.

[4] Asresie Hassen, Alemu Worku, Molla Tafere, Mekonen Tolla, Abel Ahmed, Seferew Dagnew, Yihenew G.Selassie, D. M. and T. A. (2015). Best Fit Practice Manual for Potato Production and Utilization, the 1st edition. Bahir Dar: bdu-cascape working paper 8.

[5] Food and Agricultural Organization (FAO) .2014. Asia and Pacific Food and Agriculture. FAO regional office for Asia and the Pacific. Bangkok, Thailand.

[6] Food and Agriculture Organization (FAO), 2001. Development of the cassava-processing industry and its future, pp: 330-338.

[7] CSA (2015). Agricultural sample survey report on area and production of crops (private peasant holdings, Meher season). Volume I. Addis Ababa, Ethiopia.

[8] Dagninet Amare, Geta Kidanemariam, Wolelaw Endalew, Seyife Yilma. 2015. Potato Harvester for Smallholder Producers, 3(6):103–108. https://doi.org/10.11648/j.ijmea.20150306.11

[9] Naresh. 2015. Design, Development, and Evaluation of Carrot Digger. Chaudhary Charan Singh Haryana Agricultural University, India.

[10] Ismail M. R., Yassen A., Afify M. S. 2011. Mechanical properties of rice straw fiber-reinforced polymer composites. Fibers and Polymers; 12(5): 648–656.

[11] Ktheisen. 2009. Potato production in Ethiopia. International potato center. Retrieved from: https://doi.org/potato production-pf/res5

[12] Food and Agriculture Organization (FAO), 2001. Development of the cassava-processing industry and its future, pp: 330-338.

[13] Ministry of Agricultural Development (MoAD). 2016. Potato Seed Tuber Production Techniques Manual. Sindhupalchok, Chautara, Nepal.

[14] Mcleod, C. D., Misener, G. C., Caissie, J. R. 1989. A vertical lift digger for harvesting potatoes. Canadian Agricultural Engineering, Research Station, Agriculture Canada, Fredericton, NB, Canada, 55: 11–14.

[15] Malcolm E.W., Tappan J.H., Sister F.E. 1986. The size and shape of typical sweet potatoes. Trans. ASAE. 29: 678-682.

[16] Mohsenin, N.N. 1986. Physical properties of plant and animal materials. Gordon and Breach Science Publishers, New York, USA.

[17] Isaac Bamgboye A., Adebayo S. E. 2012. Seed moisture dependent on the physical and mechanical properties of Jatropha curcas. Journal of Agricultural Technology 8(1): 13-26.

[19] Marvin, J.P., Hyde, G.M. and Cavalieri, R.P. 1987. Modeling potato tuber mass with tuber dimensions.

Transactions of the American Society of Agricultural Engineer, 30(4), 1154–1159.

[20] Khojastapour, M. 1996. Design and Fabrication Method of Potato Sorting Machine according to Iran Conditions. Master of Science Thesis, Tehran University. Tehran, Iran.

[21] Yurtlu Y. B., Yeşiloğlu E., Vursavuş K., K., Saçilik K. Coefficient of Friction Of Potato (Solanum Tuberosum L.) Tubers in Different Surfaces. ADÜZiraat Fakültesi Dergisi 2011; 8(2): 35 – 40.

[21] Yurtlu Y. B., Yeşiloğlu E., Vursavuş K., K., Saçilik K. Coefficient of Friction Of Potato (Solanum Tuberosum L.) Tubers in Different Surfaces. ADÜZiraat Fakültesi Dergisi 2011; 8(2): 35 – 40.

[22] Bentini, M., Caprara, C., and Martelli, R. 2008. Evaluation of the physical-mechanical properties of potatoes during conservation. In Innovation Technology to Empower Safety, Health, and Welfare in Agriculture and Agro-food Systems. Ragusa-Italy: Agricultural Economics and Engineering Dept., University of Bologna, via G. Fanin 50.

[23] Khura, T.K. 2008. Design and Development of Tractor Drawn Onion Digger. Doctoral dissertation, Indian Agricultural Research Institute, New Delhi, India.

[24] Pavlista, B.A.D. 2005. Potato eyes. Nebraska University. 9(3):8–9. Retrieved from: https://doi.org/HISAR – 125004 (HARYANA)/2013AE05M

[25] Sukhwinder, S. 2006. Design, development, and field testing of potato digger. *Potato Jornal of India*, 33:134–138

[26] Reddy, P., Moses, S.C. and Aalam, R.N. 2018. Performance evaluation of adjustable elevator for tractor-drawn potato digger. Int.J.Curr.Microbiol.App. Sci. 7(11): 1502-1513. Retrieved from: https://doi.org/10.20546/ijcmas.2018.711.173

[27] Arfa G. K. 2007. The effect of harvesting operation on potato crop handling. Misr J. Ag. Eng., 24(3): 492-503.

[28] Alexei S., Alexandr A., Alexei D., Andrei P.2019. Comparative study of the force action of harvester work tools on potato tubers. Research in Agricultural Engineering, 65 (3): 85–90.

[29] Wulfsohn, D.; B. A. Adams and D. G. Fredlund. 1996. Application of unsaturated soil mechanics for agricultural purposes. Canadian Agricultural Engineering 38 (3): 173-181.

[30] Tuncer B. E., 2014. Shear strength of soils, University of Wisconsin–Madison. Received from: https://www.researchgate.net/publication/255662365

[31] American Society of Testing Materials (ASTM). 1994. Annual book of ASTM standards, Vol. 04.08. Philadelphia, USA.

[32] Mehmet T., Ilker U., Murad C., Husseyn K.C. and Davout K. 2010. Design of a Horizontal Penetrometer for Measuring On-the-Go Soil Resistance. Sensors, 9337–9348. Retrieved from: https://doi.org/10.3390/s101009337. November 12, 2017.

[33] Hillel, D. 2004. Introduction to Environmental Soil Physics. Elsevier, Amsterdam, the Netherlands.

[34] Aude, G., Joe, L., Yves, D. and Carolyne, D. 2007. Effects of seedbed structure and water content at sowing on the development of soil surface crusting under rainfall. Soil and Tillage Research, 95:207–217.

[35] Khater, I. M. 2009. Effect Of Working Speeds Of Mechanical Harvesting On Potato Damage In South Eastern. Conference on Recent Technology in Agriculture. Cairo, Egypt: Agricultural Mech. The unit, Soil Conservation Department, Desert Research Center (DRC), Cairo.

[36] Skrobacki, A., Halderson, J.L., Pavek, J.J. and Corsini, D.L. 1989. Determining Potato Tuber Resistance to Impact Damage. American Potato Journal, 66:401–402.

[37] Azizi, P., Dehkordi, N. S., Farhadi, R. 2014. Design, Construction, and Evaluation of Potato Digger With Rotary Blade. Cercetări Agronomic în Moldova. 3 (159):1-7

[38] Awady, M.N., Yehia I., M. 2003. Development and theory of rice cleaner for reduced impurities and losses. Misr J. Ag. Eng. 20: 53–68. Retrieved from https://www.researchgate.net/publication/306040384

[39] Kheiry, A. N. O and Dong xing, Z. (2016). Work rate, wheel slippage, and Some Soil properties as affected by staggered reciprocating sub-soiler and tractor forward speed. Int. J. of Eng., Studies and technical Approach (IJESTA). 2 (8): 1-11.

[40] Hevko R.B., Tkachenko I.G., Synii S.V. Flonts I.V. 2016. Development of Design and Investigation of Operation Processes of Small-Scale Root Crop and Potato Harvesters. INMATEH-Agricultural Engineering, 49(2): 53–60.

[41] Abayineh Awgichew. 2015. Design and development of tef grain and chaff separating and cleaning machine. MSc thesis, Haramaya University, Haramaya, Ethiopia.

[42] Duraisamy (1997) reported that Duraisamy V.M., 1997. Investigation on the effect of soil, crop, machine, and operational parameters concerning mechanical harvesting of groundnut. The University of Coimbatore.

[43] Mahmood, R.S., Ali, E., Abbas, H. and Hoda, K. 2017. Draft force requirements of a dual bent blade subsurface tillage implement. CGIR Journal.19(1):74-80.

[44] Narender. 2012. Performance evaluation of root crop digger. MSc thesis, Chaudhary Charan Singh Haryana Agricultural University, Hisar, India.

[45] Payne, P.C.J. and Tanner, D.W. 1959. The relationship between the rake angle and the performance of simple cultivation implements. Journal of Agricultural Engineering Research, 4 (4): 32-32.
[46] Thanku T.C., Tiwari, P. S. 1994. Harvesters, Soil bin investigations, and field performance evaluation of lifting shares used on the potato. J.Agric.Engng. ISAE, XXXI: (1-4).
[47] Chase, L. W. 1942. A Study of Subsurface Tiller Blades. Agr. Engin. 23: 43- 45, 50, illus.
[48] Kawamura, N. 1952. Study of the plow shape. Society of Agricultural Machinery Journal (Japan) 14(3):65-71.
[49] Payne, P. C. J. 1956. Relationship between the mechanical properties of soil and the performance of simple cultivation implements. Journal of Agricultural Engineering Research 1:23-50.
[50] Akhir, H., Ahmad, D., Rukunudin, I. H., Shamsuddin, S., Yahya, A. 2014. Design and development of a sweet potato digging device. Pertanika Journal of Science and Technology, 22(1): 43–53.
[51] Osman, M.S. 1964. The mechanics of soil cutting blades. Journal of Agricultural Engineering Research, 9(4):313- 328.
[52] Gill, W. R., and G. E. Vanden Berg. 1967. Soil dynamics in tillage and traction. Handbook No. 316, U. S.D.A. 511pp.
[53] Hettiaratchi, D., and Reece, A. (1974). The calculation of soil passive resistance. Geotechnique, 24(3), 289-310.
[54] Godwin, R.G. and G. Spoor. 1977. Soil failure with narrow tines. Journal of Agricultural Engineering Research. 22: 213-228.
[55] McKyes, E. and Ali, O. S. 1977. The cutting of soil by narrow blades". J. Terramech. 14(2),43-58.
[56] Perumphral, J. V., Grisso, R. D. and Desai, C. S. (1983), "A Soil-Tool Model Based on Limit Equilibrium Analysis," Transactions of the ASAE, Vol. 26(4), American Society of Agricultural Engineers, St. Joseph, MI, USA, pp. 991-995.
[57] Sizov, D.A and V.A. Milyutkin. 1978. Operation of blade in the soil. Eletrifikatsiya Satialisticheskogo Sel'skogo Khozyaistva.Vses.Nauchno- issl Inst. Melch. Sel'khoz., USSR No.3: 7-8.
[58] Harrison, H. P. 1982. Soil reactions from laboratory studies with an inclined blade. Transactions of ASAE. 25(1): 7-12, 17.
[59] Stafford, J. V., and D. W. Tanner. 1983. Effect of rate on soil shear strength and soil- metal fiction. Soil and Tillage Research 3(1983):321-330.
[60] Jekendra Y. and Singh, P. 1991. Energetics of forage chopping. Agricultural mechanization in. Asia, Africa and Latin America 22(1): 59-63.
[61] Hanna, H.M; Erbach, D.C; Marley, S.J; Melvin, S.W. (1993a). Comparison of the Goryachkin theory to soil flow on a sweep Transactions of the ASAE, 36 (2):293-299, St. Joseph, Michigan.
[62] Kushwaha, R.L., Chi, L. Shen, J. 1993. Analytical and numerical models for predicting soil forces on narrow tillage tools - a review. Canadian agricultural engineering, 35(3): 183-193.
[63] Hyde, G.M and R.E. Thorntor. 1985. Potato harvester performance with rotary disk blades. Agricultural Engineering. 11(12): 432.
[64] Gupta, P. D., Gupta C. P., and Pandey K. P. 1989. Performance evaluation of wide cutting tillage tools of different geometry for dryland farming. Soil and Tillage Research, 14:145-162.
[65] Peterson, C. L., R. E. Thornton, and D. A. Smittle. 1975. The effect of some potato harvester operating variables on potato tuber injury. Circular 583, Washington State University, Pullman, WA.
[66] American Society of Agricultural Engineers [ASAE]. 2003a. D497.4 Agricultural machinery management data. p. 373-380. In: ASAE. ASAE standards 2003. ASAE, St. Joseph, MI, USA.
[67] De Baerdemaeker, J., Scheerlinck, N., Jancsok, P. and Verboven, P. 1999. Root Crops.pp.69-242. In: De Baerdemaeker, J. (ed). CIGR (The International Commission of Agricultural Engineering) Handbook of Agricultural Engineering: Agro-Processing Engineering. American Society of Agricultural Engineers, Michigan, USA.
[68] Al-Jubouri1 K. A. J. and McNulty P. B. 1983. Potato Damage And Losses As Influenced By Vibratory Digging. *Ir. J. agric. Res. 22: 243-25.*
[69] Naji Mordi N. Al-Dosary. 2016. Potato harvester performance on tubers damage at the eastern of Saudi Arabia. *AgricEngInt: CIGR Journal Open access at http://www.cigrjournal.org* (*18), 2:32-42.*
[70] Bangar, V.T., Jadhav, S.R., Patil, K.D., Biradar, V.U. and Ostwal, R.S. 2016. Design and development of potato harvester. IJARIIE, 2(3): 3343-3347. Retrieved from: www.ijariie.com
[71] Sharma, A.P., Verma, S.R. and Bansal, A.S. 1986. Design, development, and field evaluation of an oscillatory potato digger. Agricultural mechanization in Asia, Africa, and Latin America, 17(3):60-62.
[72] Kang, W.S., Halderson, J.L. 1991. A vibratory two-row potato Digger. Applied Engineering in agriculture. 7 (6): 683-687.
[73] Schweers, V. H., Tulare, C., Voss, R. E., Davis, K.B., Modoc-Siskiyou, C. Timm, H., Davis, J. B., Wright, D. N. and Kern, C. 2015. Potato Harvesting: Potato Production Series. 369, 2. Retrieved from: http://vric.ucdavis.edu/pdf/potatoes/potatoharvesting.pdf
[74] Hyde, G. M., R. E. Thornton, and D. W. Woodruff. 1983. Potato harvester performance with automatic chain load control. Trans. ASAE (Am. Soc. Agric. Engrs.) 26(1): 19-22.

[75] Al-Dosary, N.M. 2016. Potato harvester performance on tubers damage at the eastern of Saudi Arabia. CIGR Journal 18:32-42.

[76] Omer A. A., Amina I. H., Ahmed M. E., Moayad B. Z. 2017. Tractor Performance as Affected by Tilt Angle of Disc Plough under Clay Soil. Science and Technology Publishing (SCI & TECH), 1(1):13-20.

[77] Zoltán, V.I. 2015. Research on the optimum shape and size of potato ridges. University Of agricultural sciences and veterinary medicine, Cluj-Napoca.

[78] Ethiopian Institute of Agricultural Research (EIAR) (2007). Crop technologies guidelines. Amharic version. Addis Ababa.

[79] Giger, M. 1999. Avoiding the Shortcut: Moving beyond the Use of Direct Incentives—A Review of Experience with the Use of Incentives in Projects for Sustainable Soil Management. Development and Environment Reports 17, Centre for Development and Environment (CDE), University of Berne.

[80] Tewodros Mulugeta. 2017. The Effects of a Low toxicity pesticide on potato Late Blight, Tomato Leaf miner, Potato Tuber Moth and Its Major Parasitoid in Potato and Tomato Intercrops. Doctoral dissertation, Addis Ababa, Ethiopia.

[81] Diviš J., Štěrba Z. (1997): Relationship of fertilizer application and mechanical damage to potato cv. Krasa tubers. Rostlinná Výroba, 43: 199–204.

[82] Mckyes E.1985. Soil Cutting and Tillage.Developments in Agricultural Engineering,7, Elsevier, Amsterdam.

[83] Luth, H. J. and Wismer, R. D. (1971). Performance of plane soil cutting blades in the sand. Transactions of the ASAE, 15(2):0211–0216.

[84] Kepner, R.A., Bainer, R., Barger, E.L., 1978. Principles of Farm Machinery, 3rd edition. Inc. AVI Publishing Company, Westport, USA.

[85] Harrison, HP. 1990. Soil surface profile meter for simple tillage tools. Transactions of the ASAE 33(1):21-24

[86] Ros, V., Smith, RI., Marley, SJ., Erbach, D.C., 1995. Mathematical modeling and computer-aided design of passive tillage tools. Transactions of the ASAE 38(3): 675-688.

[87] Bernacki, H., Haman, J. Kanafojski, C. 1972. Agricultural machines, theory, and construction. The scientific publication, central institute of scientific, technical and economic information, (10). Warsaw, Poland.

[88] Younis, S. M., Ghonimy, M. I., Mohamed, T. H. 2006. Development of a potato digger, 23: 292–313.

[89] Kang, W. S. and J. L. Handelson .1991. "Vibratory, Two-row, potato digger" transaction of ASAE, (7).

[90] Ibrahim Issa M. I., Zhaoguo Z., Wael El-.K, Xi Yanga, Haiyi W. 2020. Design, ANSYS analysis, and performance evaluation of potato digger harvester. International Agricultural Engineering Journal, 29(1):60-72.

[91] Liao Y., Sun Y., Liu S., Cheng D. 2012. Development and prototype trial of digging-pulling style cassava harvester. Transactions of the Chinese Society of Agricultural Engineering, 28(2): 29–35. https://doi.org/10.3969/j.issn.1002-6819.2012.z2.006

[92] Primo, J. 2012. Chain conveyors, practical calculations: chain and apron conveyors: PDHonline Course M360. Retrieved from: www.PDHonline.org

[93]Tarek H. M, Mokhtar C. A., Hanafi A.R., Gaber R. G. 2016. Modifying the potato digger conveyor rolls to suit the Egyptian conditions. International Symposium, ISB-INMA- 2016, 1-16.

[94] Tikuneh D.B. 2020. Design, Construction, And Performance Evaluation Of Single Axle Tractor Pulled Potato Digger Elevator. MSc Thesis Research, Haramaya University, Haramaya, Ethiopia.

[95] Khurmi, R. S., and Gupta, J. K. 2005. Theory of machines (pp. 77-108). New Delhi: Eurasia publishing house.

[96] Hunt, R. D. 1983. Farm power and machinery management. 9th ed., Cushing-Malloy Inc., NY.

[97] Tawfik, M.A., Abdellah Y. S.. 2012. Fabricating a Prototype of Potato Digger to Suit Small Holdings. Misr J. Ag. Eng., 29(2):705 – 724.

[98] Ebrahem, I. Z., Ayman, A. E., & Guidetti, R. 2011. A New Small Potato Planter For Egyptian Agriculture: 7–13.

[99] Solomon Gebregziabher, Abdul M., M., Hendrik V., B., Herman R., Jan N., Hubert V., Mintesinot Behailu, Jozef D., Josse De B. 2006. Animal Drawn Tillage, the Ethiopian Ard Plough, Maresha : A Review. Researchgatee, 89(June), 129–143. https://doi.org/10.1016/j.still.2005.08.010

[100] AMRD (Agricultural Mechanization Research Department). 2008. Agricultural Mechanization Research Annual Report, EIAR, Addis Abeba, Ethiopia.

[101] Dixit, A. (n.d). Farm machinery and equipment. Farm machinery and power Eng., Pau, Ludhiana, India.

[102]Alamein, Ismail Alhajj Adam Alhaseen Ahmad Mohammad Saeed Sharif Zaid Muhiead Abuzaid Ali Almustafa Abdalrahman Mohamed Ahmed. 2015. —Design of a One-Row Potato Digger Harvester.The University of Khartoum.

[103] Srivastava, A. K., Goering, C. E., Rohrbach, R. P. 2012. Fruit, Nut, and Vegetable Harvesting. (P. McCann, Ed.) (2nd Ed.). USA: American Society of Agricultural and Biological Engineers.

[104] Lindsay, G. G. (n.d.). Mechanization in Potato Production Mechanisation- (2). Lincoln.

[105] Arthur W., Richard S., Moses K., Joyce B., David C., Kenneth W., Robert G. and Lawrence O. 2017. Technical report: Improved Potato Harvesting Techniques. CGIAR Research Program on Roots, Tubers, and Bananas.

[106] Ismail, Z.E., Amar, E.A., Riccardo, G. 2015. A new Small potato Planter for Egyptian Agriculture. J. of Ag. Eng. Riv. Di. Ing. Agr. 3:7-13.

[107] Kumar, D., Tripathi, A. 2017. Potato Digger Cum - Elevator, 7(2): 433–448. https://doi.org/IJASRAPR201755]

[108] Bouman, A. 1993. Proceedings of the meeting of the section engineering of the EAPR. 6-9 August 1993. A review of the research work into the different haulm killing methods in the Netherlands. Haulm killing and damaging potatoes: Wageningen, the Netherlands.

[109] Vatsa, D.K., Singh, S.P., Gupta, R.K., and Verma, M.K. 1996. Comparative studies on the performance of power tiller operated potato diggers in hills. Journal of the Indian Potato Association, 23(3/4): 121-129.

[110] Varshney, A. C., Patel, K. V. and Patel, A. S. (1989). Design and development of bullock-drawn potato digger. Agricultural Mechanization in Asia, Africa, and Latin America. 20 (1): 61-62.

[111] Kanchan, K., S., Mehta, C. R. 2016. proceeding of Asia and pacific workshop on whole process mechanization of potato production: mechanization on potato cultivation in India, on June 27-28, Kunming, China.

[112] Singh, M., Gulati, S., Singh, S. 2008. Farm Equipment and Machines for Potato Production (Technical bulletin No. 93). Retrieved from http://cpri.ernetin

[113] Anon. 1975.

[114] Tiwari R.K., Chauhan S.K., Din M., Yumnam J., (2018) Improved Potato Diggers in Terrace Condition of Sikkim in India. International Journal of Agriculture Sciences, (10)11: 6211-6214.

[115] Mohamed H. D., Abdalla N. O., Kheiry, Yuan Lliwei, Ali Musa Mohamed, Hu Jiandong. 2018. Arm Machinery Size and Cost Management System In The Rain Fed Sector Of Gedarif Area. *Global scientific journal*, 6 (10):93-102.

[116] Dijkhuis and Visser, 2002. Development of lightweight potato harvester, the Netherlands.

[117] Katiwat and Khommueng (1994) [117] Katiwat, T., Khommueng, P. 1994. Design and development of a power-tiller mounted potato digger. *AGRIS.* 1: 139-141.

[118] Verma, S.R. 1977. Performance of an experimental potato digger with an oscillating blade. Journal of Agric. Engg., 14(3): 99.

[119] Mcleod, C. D., Misener, G. C., Caissie, J. R. 1989. A vertical lift digger for harvesting potatoes. Canadian Agricultural Engineering, Research Station, Agriculture Canada, Fredericton, NB, Canada, 55: 11–14.

[120] Sunil G. Manjit S. 1999. Design and development of an oscillating type potato digger. Proceedings of the Global Conference on Potato, New Delhi, India, 2: 6-11.

[121] Singh, S. 2006. Design, Development, and Field Testing of potato diggers. 33: 134–138.

[122] Misener, G. C, McLeod, C. D. Walsh, J. R. and Everett, C. F. 1989. Effect of potato harvesting injury on post-storage marketability.

[123] Sharma, A.P, and S.R.Verma. 1986. Performance and vibration control of tractor mounted oscillatory potato digger. AMA. 17(1): 47-50.

[124] Kang, W.S., Halderson, J.L. 1991. A vibratory two-row potato Digger. Applied Engineering in agriculture. 7 (6): 683-687.

[125] Srivastava AK, Goering CE, Rohrbach RP, and Buckmaster DR, Engineering Principles of Agricultural Machines. American Society of Agricultural and Biological Engineers, St Joseph, MI, 588 pp. (2006).

[126] João, Serrano , José, Peça, Fernando, Santos. 2011. Technical paper operational performance of the mechanized and semi-mechanized potato harvest.

[127] Al-qarallah *et al.* (2012) [128] Al-qarallah, B., Hamdi, M. R., Al-hadidi, N. A. 2012. Evaluation of Labour under Manual and Mechanized Practices for Potato Production in Jordan Valley. Jordan Journal of Agricultural Sciences. 8(4):614–627.

[128] Ibrahim. M. M., Amin. E., Farag A. 2008. Developing A Multi-Purpose Digger For Harvesting Root Crops. *Misr J. Ag. Eng.,* 25(4): 1225-1239.

[129] Mckyes E. 1989. McKyes Agric Soil Mechanics. Mcdonald college of McGill Univerisity, Canada: Elsevier science publishers B.V., Amsterdam.

[130] Khadr, K.A. 2008. Effect of Some Primary Tillage Implement on Soil Pulverization and Specific Energy. Misr J. Ag. Eng., 25(3): 731-745.

[131] Macmillan, R.H. 2000. The mechanics of tractor - implement performance theory and worked examples: A textbook for students and engineers. The University of Melbourne, Melbourne, Australia.

[132] Moayad, B.Z., Ahmed, M.E., Mohammed, H.D. and Afraa, S.M. 2014. Development of powered groundnut harvester for small and medium holdings in North Kordofan state in Western Sudan. World Journal of Agricultural Research, 2(3):119–123. Retrieved from: https://doi.org/10.12691/wjar-2-3-6

[133] Pavani, 2017; [136] Pavani, J., 2017. Design, development, and performance evaluation of tractor-operated potato digger. MSc Thesis, Jabalpur, India.

[134] Sakin, R., Dumanay, A. B., Sakin, G. V. 2015. Design of a testing machine to determine certain physical and mechanical properties of hard-shelled and hard-pitted fruits, and application of olives in the Edremit Gulf region (Turkey), 752–758.

[135] Faleye et al., 2013 [137] Faleye, T., Atere, O. A., Oladipo, O. N., Agaja, M. O. 2013. Determination of some physical and mechanical properties of some cowpea varieties, 8(49):6485–6487. https://doi.org/10.5897/AJAR11.626

[136] Michael, T. and B. William. (1998). Preventing potato bruise damage. The University of Idaho. Cooperative extension system

[137] Jack, K., Dessureault M. and Prasad R. 2013. Post-Harvest Life of Organic Potatoes. Retrieved from: http:// www.escrop.com/OrganicPotatoes

[138] Alexander D.P. 2010. Potato eyes. Nebraska university. 9(3):8–9. Retrieved from: https://doi.org/hisar–25004 (Haryana)/2013ae05m

[139] Gary C; Jones J W; Tchamitchian M (1998). Crop modeling in horticulture: state of the art. Scientia Horticulturae, 74, 3–20.

[140] Sastry S. J. 2019. Blackspot Bruise in Potatoes, Crop Series, Potatoes. Fact Sheet 5.621. Colorado State University.

[141] Johnson, L.F. 1974. A vibrating blade for the potato harvester. Transactions of the ASAE (American Society of Agricultural Engineering) Journal. 17(5):867.

[142] Israil, H.M., Zakariya, H.M., Saha, K.K. 2016. Design and development of a low-cost power tiller-operated potato harvester for small farmers. Bangladesh J.Agri. Engg. 27(2):19-27. Retrieved from: https://www.researchgate.net/publication/324438232

[143] Yu Chutcheva, Zh Telegina, Dorokhov. 2019. Feasibility study of the optimal type of potato harvester for the conditions of the Moscow region. IOP Conf. Ser.: Earth Environ. Sci. 274 012045:1-8.