MACHINERY FOR PEANUT HARVESTING: A COMPREHENSIVE REVIEW
/
MAKINARYA PARA SA PAG-AANI NG MANI: ISANG KOMPREHENSIBONG PAGSUSURI

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ABSTRACT
Peanuts are an important source of oil and feed crops. It is vital to elevate the economy and feed the increasing population. Due to urbanization, the decrease and aging of the workforce threaten the agriculture sector. Consequently, countries around the world are urgently in need of innovation, particularly from an adoptable peanut harvesting technology perspective. As a result, this work focused on reviewing the developments in peanut harvesting, emphasizing the impacts of manual to mechanical harvesting methods. Specifically, mechanical harvesting is affected by soil characteristics, peanut plant characteristics, maturity at harvest, land size, peanut harvesting methods, and the importance of innovating peanut harvesting machinery. This endeavor covers legitimate scientific publications from 2010 to 2023, sustained by online public data from different government agencies. The review ends with the recommendation for standardization of peanut harvester machine specifications and testing methods to easily compare machine performances, aiding farmers, researchers, and industry stakeholders in better decisions when selecting mechanical peanut harvesters. Further, standardizing testing methods could establish operational efficiency and foster innovation and improvement within the industry.

ABSTRAK
Ang mani ay isang mahalagang produktong pinagkukunan ng langis at pagkain na may mahalagang papel sa pagpapalago ng ekonomiya at sa pagtugon sa pangangailangan ng patuloy na dumaraming populasyon. Gayunman, dahil sa mabilis na urbanisasyon, ang patuloy na pagbawas at pag-edad ng mga magsasaka ay nagdudulot ng seryosong banta sa sektor ng agrikultura. Bunga nito, may agarang pangangailangan ang bansa para sa mga makabagong teknolohiya sa pag-aani ng mani. Nakatuon ang pag-aaral na ito sa pagsusuri ng mga pag-unlad sa teknolohiya ng pag-aani ng mani, na binibigyang-diin ang paglipat mula sa manwal patungo sa mekanikal na mga pamamaraan. Tinatalakay rin ang mga aspeto na nakaaapekto sa paggamit ng makinarya sa pag-aani, kabilang ang mga katangian ng lupa, morpolohiya at antas ng kahandaan ng halaman sa pag-aani, lawak ng sakahan, at mga pamamaraang ginagamit sa pag-aani, gayundin ang kahalagahan ng patuloy na inobasyon sa makinarya. Sinasaklaw ng pagsusuring ito ang mga lehitimong publikasyong siyentipiko mula 2010 hanggang 2023, na sinusuportahan ng mga pampublikong datos na makukuha sa internet mula sa iba't ibang ahensiya ng pamahalaan. Iminumungkahi ng pag-aaral ang istandardisasyon ng mga espesipikasyon at pamamaraan ng pagsusuri ng mga makinang pang-ani ng mani upang mapadali ang paghahambing ng pagganap, mapabuti ang kahusayan sa operasyon, at maisulong ang patuloy na inobasyon sa industriya.

INTRODUCTION
Around the world, the rapid increase in human population, the influence of climate change, and the weakening of skilled laborers are some challenges besetting modern agriculture. Peanuts are one of the five most important oilseeds in the world *(Fletcher and Zhaolin, 2016; Variath and Janila, 2017)*. Peanut seeds make a vital contribution to the diet in many countries. Peanuts are rich in protein, lipids, and fatty acids for human nutrition. It is also a rich source of oil at 47 to 50% oil content *(Akhtar et al., 2014)*.

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Global production is dominated by China, India, Nigeria, and the United States, which together account for approximately 69% of total output. The production trend increased from the 1970s to 2013. The yield in 1970 increased from 0.93 to 1.64 MT/ha in 2013. It follows that the area harvested increases over time. This significant growth is attributed to acreage harvested expansion *(Fletcher and Shi, 2016).* Globally, peanut utilization is dominated by crushing for oil and meal for domestic use, accounting for approximately 86% of total production in 2013. The remaining 14% is allocated to seed use, animal feed, and post-harvest losses. In most producing countries, peanuts are primarily processed for oil, meal, or direct food consumption *(USDA-FAS, 2014)*.

Providing sufficient peanut production is of great importance. Thus, deploying interventions to increase production and avert losses from farmgate to food plate is crucial. The peanut production pipeline stated that the harvesting operation has the highest losses. Peanut harvesting is the process of digging, uprooting, field drying, and threshing/stripping of pods. This operation accumulates unexposed, uncollected, and damaged peanut pods. For labor, it accounts for more than 50% of the production process *(Gao et al., 2017).* Manual labor costs are estimated at 60% of the total production cost *(Ladaniya, 2023).*

It is impossible to generalize solving these problems, as not all farms have the same field conditions. All commercially available peanut harvesters' performance relies heavily on field conditions. Harvesting peanuts is done using different mechanical designs. The simplest is using hand-held tools involving greater human force, which is labor-intensive, higher pod loss, and time-consuming *(Chen et al., 2020; Yang et al., 2022; Shi et al., 2022).* Consequently, the development of mechanical harvesters has emerged as a replacement for manual tools and animal-drawn diggers. However, the level of mechanization varies considerably across regions: while some countries have achieved full mechanization, others remain at an intermediate stage of mechanical harvester adoption.

The first patented self-propelled peanut harvester was developed in 1915 *(Boyd, 1915),* while the tractor-driven peanut harvester was developed in 1944 *(Knowles, 1944).* This development serves as the basis for today's innovations. Despite fast modernization, limited review articles discuss the advancement of peanut mechanization. *Moreira et al., (2024)* review focused on the implications of mechanization on peanut production, emphasizing the immediate need for cost-effective and environmentally sustainable practices. Therefore, this review aims to analyze and synthesize the current state of the art in peanut harvesting machinery. Specifically, it seeks to identify key constraints affecting peanut harvesting, evaluate existing harvesting machines with respect to their design, technical specifications, and field performance, and assess existing gaps in current harvesting machinery. This review is intended to serve as a valuable resource for machine designers, policymakers, researchers, and academics across the agricultural sector, providing insights that can inform policy development and stimulate technological innovation.

REVIEW FRAMEWORK

This review comprises a hierarchy of theoretical considerations. Throughout the analysis, review stages presented in Figure 1 were implemented: (i) review protocol development for the eligibility criteria; (ii) search for research studies and selection satisfying the eligibility criteria; (iii) classical framework definition to be executed in the reference review for structure building; (iv) studies selection fitted in the category; and (v) analysis and comparison of fit studies.

For this review, the research specifically related to mechanical digging and harvesting applied in peanut production is set as a limitation. Mechanical harvesters may have been developed and tested in various environmental conditions, specifically open fields. Hence, mechanical harvester tests should be field tested in peanut farms, excluding transportation, processing, and storage. Further, the following literature eligibility criteria are: (1) the study is published in the English language; (2) the study is a research article published in peer-reviewed scientific journals; (3) articles have been published between 2010 to 2023, as any developed technology used before this review may be improved/modified. Literature published in journals, such as short communications, and developed mechanical harvesters that have not been field-tested are excluded. The review paper is to support the findings of the selected studies.

The studies included are from open online sources legitimately peer-reviewed in electronic depositories such as ScienceDirect, SpringerLink, Scopus, and Web of Science. Publications from these depositories requiring access charges are also excluded. This literature review was conducted at the end of 2023. Thus, any emerging publications that are possibly missed are beyond the boundaries of the study. Mechanical diggers and harvesters available in online sources without test methods and data analysis (promotional flyers, short specifications, etc.) are also excluded.

The absence of test procedures and performance evaluation data limits the scientific validity, comparability, and reproducibility of such sources. Including these materials could compromise the rigor of the review, as performance claims cannot be independently verified or critically assessed.

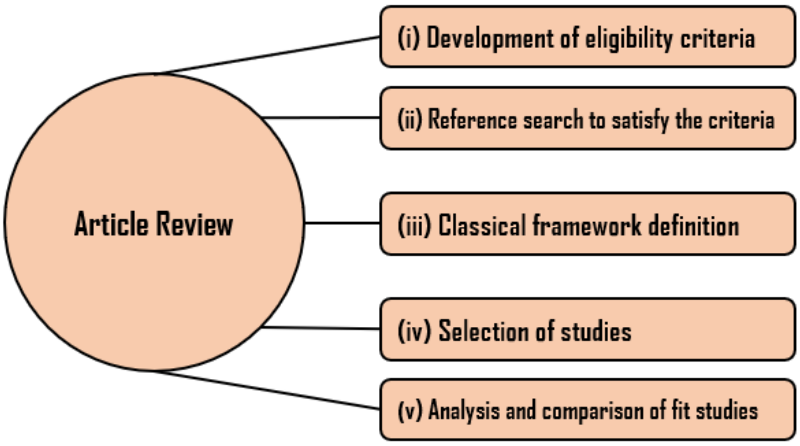

Fig. 1- Review framework for peanut harvesting machinery

PEANUT HARVESTING CONSTRAINTS

Soil Characteristics. Soil-specific moisture content plays a dynamic role in digger-related yield losses *(American Society of Agricultural and Biological Engineers [ASABE], 2020b).* Therefore, it is important to report the soil moisture content at the time of digging, as it can significantly influence machine performance *(Zerbato et al., 2013).* It was found that soils with lower volumetric moisture content during harvesting resulted in high digging yield losses and needed regular hitch adjustment at the top link. Peanuts can be grown under different land configuration methods like the flatbed method, ridges and furrows, broad bed furrow, and raised bed and furrow. Since peanuts are mostly grown in the dry season, mulching is practiced worldwide to prevent water loss by evaporation *(Sathiya et al., 2010),* suppress weed growth *(Lalitha et al., 2010),* and cut temperature fluctuations to promote soil productivity *(Sun et al., 2015)*. Mulching creates more favorable conditions for peanut growth and development, promoting efficient crop production *(Mihn et al., 2023).* It is considered a better crop management practice than conventional methods without mulching.

Soil texture is an important constraint for optimal peanut growth. Peanuts require soils with moderate aeration, adequate water-holding capacity, and sufficient nutrient retention. *Zhao et al. (2015)* demonstrated that clay soils are unfavorable for pod dry matter accumulation, while sandy soils are only conducive during the early growth stage. In contrast, loam soils are suitable for both early and late developmental stages, thereby supporting proper maturation and resulting in maximum yield.

During peanut digging, soil moisture content typically ranges from 14.26 to 22.7%, as shown in Table 1. It has been reported that mulching maintains higher soil moisture throughout the growing period, with values ranging from 14.9 to 8.2%, compared with 10.9 to 6.0% under non-mulched conditions at a soil depth of 0–30 cm. Lower soil moisture levels make it more difficult for the digger blade to penetrate the soil and effectively loosen the peanut root system. Consequently, pods remain embedded in the soil, resulting in a higher proportion of unexposed pods. At a soil moisture content of 12.4%, a digging efficiency of 90.73% was recorded, whereas at 5.9%, the digging efficiency decreased to 86.14%. Moreover, at 5.9% soil moisture content, pod loss increased to 13.87%. These findings indicate that soil moisture content directly influences both digging efficiency and pod loss *(Ademiluyi et al., 2011)*.

Several studies have estimated the cutting resistance of tillage implements using soil physical properties such as cohesion and internal angle of friction. This line of research is essential for understanding the mechanics of digger blade penetration into soil. Soil-tool interaction models are used to predict the resistive forces acting at the tip of digging tools. According to the soil-tool interaction analysis by *Patel and Prajapati (2012)*, increases in the blade-soil friction angle (Φ) and soil cohesion (C) result in higher total resistive forces acting on the digger blade. Conversely, an increase in the side internal angle of friction leads to a reduction in the total resistive force experienced by the blade. As summarized in Table 1, only *Zaied et al. (2014)* reported these parameters, with a soil cohesion of 18.3 kPa and an internal angle of friction of 20°.

Table 1

Selected studies with soil and peanut characteristics

References	Soil Characteristics				Peanut Characteristics					
	Texture	MCdb	Φ	C	Variety	Spa-cing	Height	Pod Distribu-tion	Pods/ Plant	MCdb
		[%]	[º]	[kPa]		[cm]	[cm]	[cm]		[%]
Wang et al., 2013	sandy loam	15	-	-	Yuhua 9 (erect)	25	45	16.5	32	-
Vagadia et al., 2015	medium black	14.26	-	-	GG-20 (spreading)	72	-	40	-	-
Zaied et al., 2014	clayey sand	22.7	20	18.3	-	30	25	20		
Anil et al., 2020	-	19.2	-	-	Bunch-type	30	20 to 25	16 to 20	-	-
Li et al., 2022	sandy loam	-	-	-	Yuhua 14 (erect)	75	39.7	-	40	-
Shen et al., 2023	clayey sand	-	-	-	Osmanthus 73 (erect)	45	54	-		-
Asghar et al., 2022	sandy loam	-	-	-	-	40	-	-		-
Mishamandani et al.,2014	silt loam	18.9, 19.9, & 19.3	-	-	-	75	-	-	-	49.6, 48.4, and 46.6
Ferezin et al.,2015	sandy loam	26.68	-	-	IAC 886 (spreading)	-	-	-	-	55.48
Senthilkumar et al.,2017	-	15.75 & 17.5	-	-	CO3 and TMV-7	20	31 and 24	8.0 and 6.5	-	64 and 68

Peanut Physical and Mechanical Characteristics. The knowledge of a crop's physical and mechanical properties is a blueprint for engineers in designing certain machinery. *Oliveira et al. (2020)* found that digger and harvester adjustments are made according to the characteristics of peanut plants, such as height, plant spacing, pod distribution, number of pods per plant, and pod moisture content. Other factors, such as specific gravity and density, are also essential in thermal diffusivity calculation. Shape, volume, size, color, area, and appearance of the crop are also important in the behavioral analysis for handling materials (*Atsyo et al., 2020*). Most peanut diggers and harvesters are not equipped with monitoring in real-time scenarios (monitored screen) *(Santos et al., 2016).* Thus, considering and gathering these valuable peanut characteristics results in lower losses during operation.

Referring to Table 1, the peanut's physical properties to improve a peanut digger's design were investigated. The underground pod distribution ranges from 16.5 to 20 cm for straight or non-spreading varieties and 40 cm for spreading varieties. There are 2 varieties of peanuts that are classified as spreading and non-spreading. *Shen et al. (2023)* found 62% in a 5 to 10 cm radius and 35.6% in a 10 to 15 mm radius. Only 2.7 % of pods are in a 5 cm radius near the root system. This finding recommends that the digger working width for a one-row peanut plant is at least 75 cm, with a maximum digging depth of 25 cm.

Mechanical properties are those that affect the behavior of a crop under an applied force. These properties, such as compressive strength, hardness, impact, and shear resistance, are important for designing machines for handling, threshing, and other crop processing*. Kolawole et al. (2017)* found that mechanical properties depend on crop moisture content. In the case of cassava similar to peanut as a root crop, *Oupathum et al. (2019)* found that the specific shearing energy and shearing stress increase as the cutting angle increases from 20 to 40º.

The pulling and detachment forces during harvesting are related to peanut maturity and field moisture content. The pulling force and pod cluster increase at the maturity of 127 days and decrease after the harvesting time. At maturity, the pulling force of the peanut plant with 23 stems and 35 pods is 155 and 174 N, respectively. At a peg diameter ranging from 1.90 to 2.06 mm, the detachment force reduces when the moisture content is high. Before harvesting time, the detachment force tends to increase and decrease after 127 days of maturity. The detachment force at maturity is 11.91 N *(Kurt and Arioglu, 2018).*

Liu and Sun (2020) found the physical and mechanical characteristics of peanut stalks during the harvest period. The water content was determined by dividing the stalk into three sections: a 10 cm segment from the root system (W_{lower}), a 10 cm to 20 cm segment from the middle section (W_{middle}), and the upper segment of the stalk after leaf removal (W_{upper}). It revealed that the water content is $W_{upper} > W_{middle} > W_{lower}$. The water content in the upper portion of the stalk was approximately 68%, 64%, and 57%, respectively. The friction coefficients of peanut stalks measured against stainless steel, glass, leather, and plastic were 0.680, 0.492, 0.602, and 0.556, respectively. The apparent density of the stalk was about 1.3 g/ cm^3, while the bulk density was approximately 1.1 g/ cm^3. Under a constant feed rate, the rotational speed of the cutting saw disk was 509 rad/min (81 rpm), the cutting velocity was 8 m/s, and the measured shear force was 100 N.

Mishamandani et al. (2014) reported that, at the time of digging, the moisture content of peanuts ranges from 46.6 to 49.6%, which is considered relatively high for effective separation of pods from peanut stalks. As shown in Table 1, the reported moisture content can range from 46.6 to 68%. Regardless of whether an axial-flow or tangential-flow threshing system is used, peanuts are typically field-dried or cured for 2-3 days to reduce their moisture content. In most practices, field drying is continued until the moisture content reaches 15-20%, which is considered favorable for threshing. *dos Santos (2021)* found that a moisture content within this range has an insignificant effect on harvest losses. However, it plays a critical role in reducing impurities, thereby increasing pod purity and preventing blockages in conveyors and threshing cylinders. Impurity-induced clogging can interrupt the rotation of these components, ultimately reducing operational efficiency.

Maturity of Peanut During Harvest. Assessing peanut maturity before harvesting is important to the economic viability of production. Research proves that high losses are caused by manual harvesting operations, but can reach 40% at harvesting dates beyond optimal maturity *(Gulluoglu et al., 2016). Kaba et al. (2014)* reported that harvesting peanuts too early caused a 15% decrease in yield and 21% in economic value. During the growth period, total pod production continually increased, but it reached a peak yield and then declined due to field losses when harvested over a longer period. Thus, the appropriate time of harvest must be taken seriously. *Gulluoglu et al. (2016)* investigated the pod yield of Halisbey peanut (*Arachis hypogaea var. hypogaea*), a Virginia market-type variety of 6 harvesting dates, 148, 156, 164, 172, 180, and 188 days after planting. With respective days after planting, the pod yield per plant is 63.35, 69.24, 77.50, 81.29, 87.58, and 80.82 g. The pod yield increased until 180 days after planting and decreased at 6.67 g at 188 days after planting. This indicates that harvesting is recommended at 180 days.

Pod losses of about 20 to 30% due to sprouting of peanut seed are substantial during late harvesting. Also, premature harvesting of peanut pods lowers the yield, oil content, and seed quality because of immature pods and seeds. *Seutra Kaba et al. (2014)* report that harvesting peanuts too early can reduce yield and economic value by 15 and 21%, respectively. Harvesting when 75 to 80% of pods have turned dark inside the shell is proven to give the best grade and yield. High digging loss is unavoidable when the pegs are weakened due to over-maturity or premature defoliation caused by disease, or when the soil is very dry and hard *(Jordan et al., 2013).* This signifies that harvesting peanuts at physiological maturity is advisable to obtain maximum pod yields. Further delay causes a decrease in pod yield, thereby affecting the economic viability of production.

Land Size. Of the estimated 570 million farms in the world, 74% are located in Asia. The majority are located in lower-income countries (36%) and upper-middle-income countries (47%). Out of 111 countries, 70% of farms are smaller than 1 hectare, 12% are 1 to 2 hectares, and 10% are between 2 and 5 hectares. Farm areas larger than 5 hectares are only 6% *(Lowder et al., 2016). Hazell et al. (2010)* and *Wiggins et al. (2010)* support this claim that worldwide there are 500 million small farms with less than 2 hectares.

One limitation to the introduction of mechanized crop production is the small size or fragmented fields for efficient use of machinery. Often, a field that has a total area of 1 to 2 hectares or more is commonly divided into many fields. As an example, *Xangsayasane et al. (2019)* conducted a study to determine the effect of harvester efficiency on farm size. A typical 1.9 hectare is divided into traditional small fields of 0.05 to 0.1 hectare and an optimal size of 0.2 to 0.3 hectare. The time spent to harvest rice is 5 hours for small fields and 3 hours for optimal-size fields. The longer harvesting duration for small fields is due to more turns and moving between fields. *Islam et al. (2020)* prove that even small or mini-combine harvesters with 2 m operating width worked at full capacity on larger field sizes due to fewer turns. The highest field efficiency was obtained at a field size of more than 0.2 ha, and the lowest at a field size lower than 0.08 ha. The mini-combine harvester breakeven was found at 20 to 35 ha *(Akhter et al., 2024; Hansan et al., 2029; Amponsah et al., 2017)*. This implies that a harvester must operate above 35 ha/y to generate a profit.

PEANUT HARVESTING METHODS

Hand Harvesting. Manual harvesting is a traditional and common method for crop harvesting. In root crops such as peanuts, manual harvesting involves uprooting or pulling by hand, collecting, and threshing or impact method (banging against hardwood and stone), and the use of a big basket or sack to collect detached pods from the impact. Upon uprooting and collection, the peanut plants are either immediately threshed or dried for 2 to 3 days to reduce the moisture content for easy threshing *(FAO, 2018; Attanda et al., 2022; Shen et al., 2023)*. In most developing countries, field drying is practiced to reduce losses from rotting, molds, and termites. The time spent on hand digging is 300 to 400 h/ha. It is tedious, time-consuming, and labor-intensive *(Okello et al., 2010; Mishamandani et al., 2014; Judith et al., 2022; Lavanya et al., 2022)*. Hand uprooting has a capacity of 0.006 ha/h *(Taghinazhad and Rahmani, 2023).*

Fig. 2 - Hand harvesting of peanuts
(photo courtesy of https://www.iaea.org/newscenter/news/sri-lankan-farmers-benefit-from-mutation-bred-groundnut-for-25-years and https://www.statesboroherald.com/local/business/farmers-fear-worker-shortage/)

Semi-Mechanized Harvesting. The semi-mechanized method still involved hand uprooting or using an animal-drawn moldboard plow. After field drying, uprooted peanuts are manually collected and mechanically threshed. Animal-drawn plows usually have a V-shaped ridge share to expose the root system of peanut plants to the surface. Lifter rods positioned behind the share are spaced to allow the peanut plants to be uprooted and brought to the soil surface, after which they are manually collected and threshed using strippers or threshers. *Attanda et al. (2022)* used a pair of bullocks for pulling a peanut digger. It is designed with a draft pole, cutting blade, depth control wheel, frame, and handle. To separate pods from peanut plants, *Abdi et al. (2022)* developed a tractor-driven axial current thresher with a 2 m long helical threshing unit. The peanut plants were completely fed in the threshing unit, and their pods were completely separated from the plants. After threshing, pods with high impurities, such as peanut leaves, soil, gravel, etc., are cleaned using a peanut pod cleaning device *(Zhu et al., 2023)*. The pods with impurities are placed in the collecting bin, and the outlet causes the peanut pods to fall into the reciprocating reversible long-mesh cleaning sieve for separation.

Fully Mechanized Harvesting. A fully mechanized harvesting operation involves minimal or no manual intervention, with labor primarily required only for operating the harvesting machinery. In such systems, mechanical power is applied throughout the entire process, from digging to pod threshing or stripping. However, most previous approaches have implemented only the second and third harvesting stages, as shown in Table 2. The second stage combines digging and field drying, while the third stage integrates collection and stripping. Recently, *Chen et al. (2022)* introduced peanut stalk cutting prior to digging, thereby adding a new initial stage to the harvesting process. This practice increases the pod-to-stalk ratio, reduces power requirements during threshing, accelerates field drying, and minimizes stalk and leaf impurities. In addition, peanut stalks are rich in nutrients and can be utilized as livestock and poultry feed *(Wang et al., 2022)*, enhancing the overall economic value of the crop.

Second-stage harvesting is termed "digging–laying–field drying". After the peanut plants are mechanically uprooted, they are laid in a windrow and sun-field dried for 2 to 3 days *(Prestes et al., 2019).* Research proves that field-drying to reduce the moisture content from 50% to 20% significantly decreases hull damage, loose-shelled kernels, and shelling damage (splitting and skinning) *(Roberson, 2023).* After field drying, the succeeding process, called the third stage, is the collection of dried peanut plants and separating pods.

These harvesting stages could utilize one or two harvesting machines to complete the operation. One harvesting machine refers to a combine harvester that combines the processes of digging, collecting, and stripping. While two harvesting machines are two separate machines for digging and threshing *(Bader, 2010).* Diggers and combine harvesters could either be self-propelled or tractor-drawn. Referring to Table 2, *Wang et al. (2022)* developed and studied a self-propelled combine harvester, while 8 studies were tractor-drawn diggers. For example, the combine harvester developed by *dos Reis et al. (2022)* is tractor-drawn, which means PTO drives all the moving mechanisms for digging, collection, and stripping.

Table 2

Selected studies with specified harvesting stages

References	Country	Harvesting machines	Harvesting stages				Power Source	
			1st	2nd		3rd	Tractor-Mounted	Self-propelled
			Stalk Cutting	Digging	Field Drying	Threshing		
Mishamandani et al., 2014	Iran	1	-	√	√	-	√	-
Zaied et al., 2014	Sudan	1	-	√	√	-	-	√
Asghar et.al., 2022	Pakistan	1	-	√	√	-	√	-
Vagadia et al., 2015	India	1	-	√	√	-	√	-
Antonio et al., 2018	Brazil	1	-	√	√	-	√	-
Noronha et al., 2018	Brazil	1	-	√	√	-	√	-
Anil et al., 2020	India	1	-	√	√	-	√	-
Wang et al., 2022	China	2	-	√	√	√	-	√
Chen et al., 2022	China	2	√	√	-	√	√	√
Wang et al., 2022	China	1	-	√	√	√	-	√
Li et al., 2022	China	1	-	√	√	√	-	√
dos Reis et al., 2022	Brazil	1	-	√	-	√	√	-
Shen et al., 2023	China	2	-	√	√	√	-	√

Peanut Harvester Designs and Performance Specifications. The first patent for a peanut harvester, specifically a self-propelled combine harvester, was developed by *Boyd (1915)*. This early design combined a plow and a revolving rake to uproot peanut plants. The uprooted plants were then transported by a conveyor system and passed through a transverse arrangement of longitudinal stripping fingers, which separated the pods from the root system. Both the conveyor and the revolving rake were mechanically driven by the forward motion of the rear wheel.

The first design patent for a tractor-driven peanut digger was developed by *Knowles (1944)*. This invention described a simple and efficient digger capable of two-row peanut harvesting. The machine consisted of an underground digger hitch-mounted to a four-wheel tractor, equipped with steering wheels and a pair of rear running wheels positioned at the ends of the drive axle. It incorporated a cultivator-type blade that functioned as the digging tool, along with a chain-and-sprocket-driven conveyor system that transported the uprooted peanut plants to one side of the field. Later, *Whitfield (1969)* introduced a peanut digger–shaker unit attached to a tractor, comprising side-by-side crop-elevating rattlers. The design included a pair of plows for digging, which were connected to the rattler framework, as well as coulters for cutting peanut stems. After cutting, the plants were lifted from the soil, and the rattlers shook the root systems before depositing them onto the soil surface. These early design patents laid the foundation for subsequent technological advancements in peanut harvesting machinery.

Table 3 specifies the representation of the different designs of peanut diggers and harvesters recently available and being utilized worldwide. These are self-propelled or tractor-driven peanut diggers and combine harvesters (*Kashti et al., 2011; Gao et al., 2015; Shi et al., 2022; Yang et al., 2022).* The design features summarize the lifting of peanut plants from the soil, the collection, and conveying of peanut plants to the threshing chamber for pod collection. The performance findings for Actual Field Capacity (AFC) range from 0.09 to 0.84 ha/h. The lowest AFC of 0.09 is the performance of a tractor-driven peanut digger *(Anil et al., 2020).* The highest AFC of 0.84 ha/h is also a tractor-driven peanut digger *(Shen et al., 2023).* The lifted peanut plants are arranged in the windrow for field drying, and another machine performs collection and threshing. The *Li et al. (2022)* combine harvester has a lower AFC of 0.4 ha/h. However, it combines the operation of digging, collection, and threshing, without field drying, making it faster and more efficient. *Senthilkumar et al. (2020)* designed a self-propelled peanut collector and thresher with an AFC of 0.12 ha/h. With this, the peanut plant is dug by diggers and field-dried. After 2 to 3 days, it is collected and threshed.

Table 3

Selected studies with design features and performance specifications

References	**Design features**	**Featured actual images**	**Major findings**		
			AFC [ha/h]	**FE [%]**	**Loss [%]**
Wang et al., 2013	4HLB-4 half-feed combine harvester starts operation with digging to break the main root and loosen soil, and then pulled by vertical clamping at an adjustable height of 16 to 25 cm, immediately conveyed and fed into the peanut picking device, cleaned pods are delivered into the peanut box and plant system, and other debris is thrown in the grass-throwing conveyor chain				2.05
Vagadia et al., 2015	The digger is composed of the main frame, digging blade harrow, power transmission from the PTO shaft, and shaking attachment. The digging blade is mounted on the bottom of tines, having a cutting width of 120 cm. The pod distribution lies at a 38 cm radius, the digging blade is at 45 cm width side to side, ensuring full penetration within rows.		0.35	80.0	10
Zaied et al., 2014	The riding-type peanut digger designed for small farms has a total weight of 86 kg. It is equipped with 2 digger rakes penetrating the soil mass. A 90-cm rotating cylinder with pegs to invert the peanut plants in a windrow.		0.18	84.5	

References	Design features	Featured actual images	Major findings		
			AFC [ha/h]	FE [%]	Loss [%]
Anil et al., 2020	The digging blade digs the plant out of the soil along with the pods. The conveyor helps to convey the dugout plants from the soil, shakes loose the adhering soil, and conveys them to the back of the machine, forming a row. The conveyor runs on two pairs of chain pulleys, which derive their drive from the power transmitted from the tractor PTO to the implement.		0.09	80.47	4.73
Li et al., 2022	The centering device separates the peanut plants while the gear rotates toward the peanut plants. The peanut plants are lifted and gathered into a central position while the excavating device breaks the peanut's main roots and loosens the soil. During the clamping and conveying process, the soil removal device reciprocates left and right to remove soil and impurities from the root system of the peanut plant.		0.4		2.8
Shen et al., 2023	As the peanut digger-inverter driven by a tractor moves forward, the digging shovel first breaks ridges and digs, and the soil is separated through the loop conveyor chain, and finally, the inverting roller and inverting rod are spread in the field.		0.84		
Asghar et al., 2022	The major components of the AMRI tractor-mounted peanut digger are the cutting blade, front roller, double-conveyor, and supporting bars. It is capable of performing two functions: digging and shaking.		0.27	89.31	5.55
Senthilkumar et al., 2017	The self-propelled collector and thresher harvester consists of a single-cylinder water-cooled engine as a prime mover; a chain and sprocket power transmission system, 2 flat blades of 23 × 10 × 0.6 cm in size adjustable shank-digging assembly, two 8 cm width vertical conveyor spaced at 4.7 cm gathering system, chain conveyor system, two counter-rotating stripping drums of 56 × 6.0 cm (diameter) stripping system, and sieve cleaning system with blower and oscillating sieve.		0.12	79.9	20.07

Peanut Harvester Technical Specifications. When harvesting peanuts, a common design parameter can be adjusted in the field to optimize the operation performance. The design of the machine can influence the optimal parameters. The number of rows is the number of peanut plants per hill, influencing the working width of the harvester. The forward speed is the velocity of the machine as it moves along the field during operation. The digging depth and tilt angle are characteristics of the digger blade to penetrate the soil and dig out the peanut root system. These are the considered parameters, as the largest losses in mechanical peanut harvesting occur during the stage of digging *(Zerbato et al., 2013; Mareppa et al., 2021)*. Referring to Table 4, recent literature developed diggers and harvesters have several rows varied from 2 to 8, forward speed from 1.5 to 4.68 km/h, working width from 60 to 180 cm, digging depth from 12 to 25 cm, and a digging blade tilt angle of 12º.

As much as machine specifications influence the optimum performance of the harvesters, the main criterion is the specific needs of farmers. These needs are to reduce losses during harvesting while increasing the harvester's digging efficiency. Varying the speed of operation can result in a variety of outcomes. The traveling speed is the greatest influence on the rate of peanut stalk inverting and the rate of pod loss (*Yu et al., 2016; Tian et al., 2018; Zhen, 2022*). When the forward speed is high, peanut stalks block the conveyor and are not conducive to flipping. When the speed is low, the number of peanut stalks is small, and the peanut stalk cannot stand independently for inversion. For example, *Shen et al. (2023)* proved that when the forward speed (V) of a tractor-driven peanut digger was 2.52 km/h, the inverting rate was 71.07% and the buried pod loss was 0.20%.

At 4.68 km/h, the inverting rate was 74.29%, and the buried pod loss was 0.14%. In terms of digging efficiency, *Asghar et al. (2014)* found that varying speeds of peanut digger from 1.82, 1.85, and 2.13 km/h, the best digging efficiency was 89.31% and irrecoverable loss or pod loss at 5.55% at a forward speed of 1.85 km/h. Said forward speed is more fuel-efficient and consumes less fuel. *Anil et al. (2020)* found that at an optimum digging depth of 13 cm, with a forward speed of 1.5, 2.0, and 2.5 km/h, the digging efficiency was 84.18, 85.26, and 86.36%. The pod damage loss was found at 4.37, 4.37, and 4.73%, respectively.

In hard, dry soil, digger blades may not maintain an even depth. This will result in breaking peanut pods, buried pods, and falling pods. Literature indicates that when the digging depth is optimized, it allows the blade to sever the peanut taproot an inch below the pods, without breaking the pods *(Kirk et al., 2014)*. Proper digging depth is optimal for peanut yield recovery. Referring to Table 4, references indicate digging depth, and searchable literature comparing the variable depth affecting yield recovery. In a tractor-driven peanut digger, proper digging depth is achieved in adjustment on the three-point hitch center link or the top link. When the top link is retracted or shortened, it establishes a more aggressive digging angle, which achieves deeper blade penetration. When a top link is extended or lengthened, it reduces the digging angle, resulting in shallower blade penetration. Too shallow and too deep digging penetration results in high pod losses *(Roberson et al., 2021; Kirk et al., 2014)*.

Table 4

Selected studies with technical specifications

Publication	Power	Tractor	Number of rows	Forward Speed	Working width	Digging depth
	[hp]	[hp]		[km/h]	[cm]	[cm]
Vagadia et al., 2015	-	35	5	3.67 to 3.91	120	12
Zaeid et al., 2014	-	33	-	2.54	87	15
Anil et al., 2022	-	-	2	1.5, 2.0 and 2.5	60	13
Shen et al., 2023	-	95	-	2.52 to 4.68	180	25
Mishamandani et al., 2014	-	-	-	1.4, 1.8, and 2.2	-	-
Ferezin et al., 2015	-	123	-	-	180	15
Senthilkumar et al., 2017	24	-	-	2.00	-	15
Zerbato et al., 2013	-	125	6	-	180	15
Shi et al., 2022	157	-	8	4.32	-	-
Kim et al., 2015	60	-	2	2.77	60	20

Modern Peanut Harvesting Importance

Comparison Between Manual and Mechanical Harvesting. From a hand-digging capacity of 0.006 ha/h, animal-drawn diggers have a capacity of 0.16 ha/h *(Taghinazhad and Rahmani, 2023)*. *Mishamandani et al. (2014)* compared manual with mechanical operation using a tractor-drawn digger. It showed that manual operation has a harvesting loss of 20.23% and a digging capacity of 0.014 ha/h, while mechanical operation has a harvesting loss of 3.49% and 0.154 ha/h, respectively. In terms of losses, *Mishamandani et al. (2014)* found the highest manual loss of 20.23%, and *Tibagonzeka et al. (2018)* of 12.27%. While using a mechanical digger, *Asghar et al. (2014)* revealed a loss of 5.50%, *Mishamandani et al. (2014)* of 3.49%, and *Li et al. (2022)* of 2.80%. Using mechanical harvesting saves 94% of labor and 60.5% of operation costs compared with hand digging. Nearly 50 to 60% of labor costs can be saved through mechanical stripping. Mechanical digging is 11 times faster than manual operation.

Comparison Between Existing Mechanical Diggers and Harvesters. The existing mechanical diggers and harvesters are mostly drawn by a four-wheel tractor, and only a few are self-propelled. The tractor standard Power Take-off (PTO) has recommended thrust forces *(American Society of Agricultural and Biological Engineers [ASABE]; 2020a)*. Trailed peanut harvesters have only one axle, and motion is transmitted from the tractor's PTO. The working parts are driven by hydrostatic transmissions, with motors that can reverse their direction of rotation to remove any blockage. It is aligned automatically along the row by an electrical-hydraulic control, which adjusts the coupling bar. The following are Type 1 with a drive shaft, rated engine speed, PTO power, and thrust of 35 mm, 540 rpm, ≤87 hp, and 13 kN, respectively. Type 2 is 35 mm, 1,000 rpm, ≤174 hp, and 14 kN, respectively. Type 3 is 45 mm, ≤402 hp, and 20 kN, respectively. And Type 4 is 57.5 mm, 604 hp, and 24 kN, respectively.

Referring to the specification of tractor-driven peanut diggers in Table 4, the specified tractor powers are 33, 35, 95, 123, and 125 hp. Since PTO is lower than the tractor power, the utilized tractors belong to Types 1 and 2.

The self-propelled peanut harvesters may have two-wheel or four-wheel drive, with mixed transmission to the driving wheels from a hydrostatic engine, mechanical differential axles, and two to four-speed gearboxes. Diesel engines are used, either aspirated or turbocharged. In the case of two to four rows of self-propelled peanut harvesters, both bunker-hopper discharge elevator-equipped versions are supplied. A self-propelled peanut harvester that lifts uprooted peanut plants from unspoiled tilth offers advantages under unfavorable harvesting conditions. However, their high performance requires the permanent availability of transport vehicles and a store-filling technique with a sufficient capacity if peanuts must be stored afterward.

FUTURE WORK IN PEANUT HARVESTING

An understanding of peanut characteristics is key to designing harvesting machinery. From the paper publications, the variety, plant spacing, plant height, pod distribution, pods/plant, and MC are incompletely specified. For example, out of 10 selected publications, only 3 consider moisture content during harvest *(Mishamandani et al., 2014; Ferezin et al.,2015; Senthilkumar et al., 2017*). Regarding the number of pods/plants for the design capacity of the threshing chamber, out of 10 publications, only 2 publications were disclosed (*Wang et al.,2013; Li et al.,2022*). This scenario is the same with soil characteristics. The identified parameters of soil texture, MC, internal friction angle, and cohesion are incompletely specified. Since the peanut needs to work in a maximum depth of 20 cm, the internal angle of friction and cohesion are significant in the design of soil-tool interaction forces.

Some references appear to contradict one another. However, the design of peanut harvesters is specific to the field conditions. For example, *Zhao et al. (2015)* proved that clay was unfavorable to pod dry-matter accumulation. Sand is only conductive in the early growth period. Only loam soil is suitable for both early and late period maturation of peanuts, giving the maximum yield. However, *Zaied et al. (2014)* and *Shen et al. (2023)* revealed that peanut thrives in clayey sand soil. Clayey soils were characterized by higher compaction and stickiness, posing challenges in penetration, and may result in increased soil attachment to harvested peanuts, potentially impeding machine performance. The soil moisture content associated with different soil textures also plays a crucial role, affecting the adaptability of harvesters and necessitating adjustments for optimal performance. *Ferezin et al. (2015)* reported a soil dry bulb moisture content of 26.68%. While *Wang et al. (2022)* of 15%. A high moisture content of 26.68% can lead to challenges such as mud formation, reduced traction, and increased soil adherence to peanuts, thereby reducing operation efficiency and increasing pod losses.

In all reviewed research articles, the standard testing methods were not discussed. Searching for the standard test method for peanut diggers and harvesters online is unavailable. Only the *Indian Standards (1985)* for the peanut digger-animal drawn test codes are available. However, most references use engine-powered mechanical diggers. Some other crops, such as potatoes, have tractor-operated potato diggers, shakers, and standard test methods specified in *Indian Standards (1993)*. Harvesting rice has the *International Standard Organization (2021a)* specifying the procedure and performance assessment of combine harvesters. This applies to either self-propelled or tractor-trailered type combine harvesters. It encompasses both functional and capacity tests. Specifically, this includes tests conducted over an extended period to evaluate ease of operation, adjustability, work rate, and overall operating characteristics, as well as tests performed at specific times to assess grain loss and capacity features. Harvesting forage has the *International Standard Organization (2021b)* specifying the test methods for forage harvesters. The specification covers evaluations of forage harvester function and performance, covering forage harvesters that cut the crop directly at full width or from spaced-apart plant rows or pick up pre-cut crop. The forage harvester standard can be tractor-mounted, trailed, or self-propelled.

Developing standardized test methods ensures consistency and reliability in evaluating field performance. It provides a common ground for comparison, aiding farmers, researchers, and industry stakeholders in making informed decisions about selecting and purchasing mechanical diggers and harvesters. Moreover, standardized test methods contribute to the establishment of benchmarks for efficiency, safety, and environmental impact, fostering innovation and improvement within the industry. Also, the standard specifications of peanut diggers and harvesters are not specifically disclosed. The development of standard specifications ensures uniformity, quality, and interoperability within the agricultural machinery sector.

Standardization establishes common criteria and performance benchmarks that manufacturers can adhere to, streamlining the production process and fostering innovation. Farmers benefit from this consistency as they can make more informed decisions when selecting equipment, ensuring that their chosen diggers and harvesters meet recognized industry standards for efficiency, safety, and reliability. Standard specifications also facilitate regulatory compliance, promoting environmentally friendly and sustainable practices.

The future development of peanut harvesting machinery should emphasize engineering-driven technological innovations that enhance operational efficiency, reduce environmental impacts, and address increasing labor constraints. Future research should prioritize the integration of precision agriculture technologies, including soil and crop sensors, Global Positioning System-based guidance, and machine learning algorithms, to support real-time monitoring and adaptive control during harvesting operations. Specifically, sensor-assisted systems may be developed to automatically adjust digging depth, forward speed, and conveyor operation based on soil moisture, crop maturity, and field variability, thereby reducing harvesting losses and improving overall yield recovery. In addition, future studies should focus on the standardization of performance evaluation protocols for sensor-integrated peanut harvesters to validate their effectiveness under varying field conditions. Sustainable design considerations must also be embedded in future machinery development, including low-compaction undercarriage systems, fuel-efficient power transmission, and modular designs using locally available and easily replaceable components to enhance maintainability and affordability, particularly in developing regions. Innovations addressing the utilization of peanut stalk residues generated during harvesting, such as their conversion into animal feed, bio-based materials, or energy source should also be pursued to reduce waste and improve the environmental sustainability of peanut harvesting systems.

CONCLUSIONS

Peanut harvesting is a multifaceted problem as the optimal solutions are location-specific. Crop parameters, soil characteristics, and technical specifications contribute to effective and impactful harvesting techniques. In the reviewed studies, the highest automation level is fully mechanized harvesting, from manual operation to peanut diggers and harvesters. It has evolved from digging to breaking up the soil, uprooting the peanut root system, and pod stripping. Additionally, 2 to 3 days of field drying after uprooting have been proven to be efficient. Cutting of the peanut stalk before digging is also studied, resulting in low field efficiency and unacceptable pod losses. Standard test methods are available for the harvesting of many crops; however, no standardized testing protocols currently exist for peanut diggers and harvesters. Most of the reviewed studies did not report the use of standardized test procedures. As a result, the reporting of technical specifications, field performance, and operational recommendations remains inconsistent and often incomplete. This highlights a significant gap in the standardization of peanut harvesting machinery.

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