PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(2): 1-11
https://doi.org/10.14719/pst.7539

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REVIEW ARTICLE

A review on machineries used for turmeric cultivation in India

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OPEN ACCESS

ARTICLE HISTORY
Received: 31 January 2025
Accepted: 07 March 2025
Available online
Version 1.0 : 22 April 2025
Version 2.0 : 30 April 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Yadhukrishnan B, Dhananchezhiyan P, Kavitha R, Surendrakumar A, Ashokkumar G. A review on machineries used for turmeric cultivation in India. Plant Science Today. 2025; 12(2): 1-11. https://doi.org/10.14719/pst.7539

Abstract

Turmeric is a prominent spice that is cultivated throughout India. India holds a prime position in the world turmeric industry. The activities included in turmeric cultivation, like land preparation, planting, weeding and digging, demand intensive labour. Mechanizing the turmeric cultivation is important to minimize labour requirements and production cost while enhancing the yield quality. Unlike other crops, mechanization of turmeric cultivation is still lagging. To understand the mechanization level of Indian turmeric cultivation, a study was conducted. Literature relevant to turmeric cultivation in India was identified. Since the research exclusive for turmeric is limited, ginger, which shares common properties with turmeric, was also considered for the study. Technologies involved in land preparation, planting and harvesting were identified. The current study aims to analyze the available machineries and compare their machine parameters. Land preparation is being done by common tillage implements like mould board plough and cultivator, without any special equipment optimized for turmeric. Turmeric planting and harvesting are mainly being done by manual work. It is inefficient and causes physical impacts to the labourers. Machinery used for planting and harvesting can be classified based on power sources. Available turmeric planters and harvesters are powered by bullock, power tiller and tractor. Turmeric harvesters just dig out the rhizomes and leave them in field. Later they are collected and cleaned manually diminishing the economic benefits of the mechanical harvesting.

Keywords

digger; harvester; planter; rhizome; root crop; turmeric

Introduction

India, which is considered as the origin place of turmeric, is a leading contributor to the global turmeric industry. The country is the prime producer, utilizer and exporter of turmeric worldwide (1). In the period 2022 -2023, India produced 1.16 million tonnes of turmeric from 0.32 million ha of cultivated land, accounting for over 75 % of global turmeric production. Turmeric covers approximately 6 % of India's total spices grown area (2). The largest producing states of turmeric are Maharashtra, Andhra Pradesh and Odisha. Table 1 shows the major Indian states contributing to turmeric production during the period 2022-2023 (3). The global curcumin market was 93.24 million USD in 2024 and is anticipated to grow further to 101.67 million USD in 2025 and to 205.48 million USD by 2032 (4). Fig. 1 outlines the export data for turmeric from India to key international markets during the period of 2023-2024. During this timeframe, India exported approximately 162000 tonnes of turmeric globally. Bangladesh accounted for 23 % of these

Table 1. The primary states contributing to turmeric production in India during the period 2022-2023 (3)

State	Area (1000 ha)	Production (1000 Mt)	Productivity (Mt·ha^{-1})
Andhra Pradesh	33.42	73.52	2.2
Assam	17.56	23.33	1.33
Karnataka	19.57	119.39	6.1
Madhya Pradesh	22.42	82.43	3.68
Maharashtra	88.32	323.22	3.66
Odisha	31.24	69.1	2.21
Tamil Nadu	24.75	136.37	5.51
Telangana	22.74	173.61	7.63

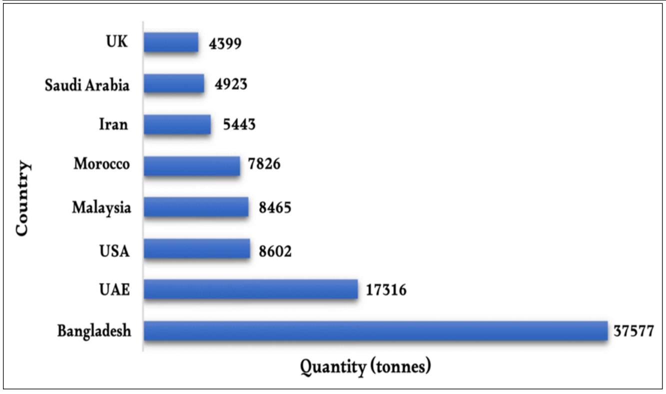

Fig. 1. Percentage of Indian turmeric export during 2023-2024 (5).

exports, importing 37577 tonnes, making it the largest importer of Indian turmeric (5). Other significant importers included the United Arab Emirates (UAE), United States of America (USA), Malaysia and Morocco (6).

Turmeric (*Curcuma longa*), a perennial spice belonging to the Zingiberaceae (ginger) family, is primarily valued for its underground rhizome, which features a distinctive branching structure and a characteristic brownish-yellow coloration (7). The turmeric plant typically attains a height of 600-900 mm, with a short pseudo-stem and elongated leaves. Turmeric holds considerable significance in both daily life and various industries. Its medicinal properties include anti-inflammatory, anti-allergic, antihypertensive, antiseptic, antioxidant, anticoagulant, antidiabetic, antimicrobial, anti-ulcer, antifertility and wound -healing effects (8). On average, Asian populations consume 0.5-1.5 g of turmeric per day, a dosage that is considered non-toxic (9). Turmeric-based pesticides are particularly promising for the protection of stored commodities, greenhouse crops, high-value row crops and for use in organic farming systems (10).

Despite the increasing production of turmeric in India and globally, the global curcumin market faces challenges due to uncertainties in the availability of turmeric as a raw material (11). Encouraging turmeric cultivation can enhance foreign trade opportunities and improve the financial conditions of turmeric farmers (12). Current turmeric production levels, however, are insufficient to meet market demand. In India, low productivity and high production costs discourage farmers from expanding turmeric cultivation. The primary cost components include manual labour, fertilizers, planting materials and animal labour. Most of the agronomic practices *viz*., land preparation, planting, weeding and harvesting, are labour-intensive (13). Although India is the world's leading producer of turmeric, the level of mechanization in turmeric cultivation remains limited. To improve productivity while reducing production costs, intensive mechanization is crucial. Given the labour demands of planting and harvesting, the development of innovative and efficient mechanized methods for these processes is of critical importance.

The increasing demand for mechanization underscores the necessity of a thorough understanding of existing machinery to support turmeric farmers. This study evaluates the availability and application of machinery across various stages of turmeric cultivation, including land preparation, planting and harvesting. An assessment of the current state of mechanization in the field is critical for formulating strategies to enhance mechanization in turmeric production.

Methodology

This article examines different methods and machinery used in turmeric cultivation. Due to the limited availability of research specific to turmeric, studies on ginger *(Zingiber officinale)* were also included, as turmeric and ginger belong to the Zingiberaceae family and share similar physical and agronomic characteristics. These shared traits allowed for the expansion of the scope of analysis. This study reviewed literature from the Web of Science and Google Scholar databases, while statistical data on turmeric production and export was collected from 'indiastat'. All research articles were sourced from peer-reviewed journals, while other data were obtained from reliable sources, including government organizations. A total of 110 research articles were analyzed, with 62 selected for inclusion based on their relevance to turmeric mechanization. The major articles were from the period of 2005-2025. The selection criteria focused on the scope of research and its contributions toward advancing mechanized turmeric cultivation.

Turmeric cultivation in India

Turmeric cultivation in India has a rich history spanning over 4000 years, originating during the Vedic era (14). It is grown across the country, from the southern states to northeastern regions, with the use of diverse cultivars tailored to local conditions. This has resulted in significant variability in morphological traits, yield attributes and quality parameters. Turmeric thrives in a variety of soils, including sandy loam, clay loam and alluvial soils. Globally, the two dominant Indian varieties are "Madras" and "Alleppey" (15). The selection of planting material plays a pivotal role in determining plant vigour, yield and production costs (16). However, turmeric cultivation is highly labour-intensive, requiring approximately 207.79 human labour days per production cycle (17). A study conducted in the state of Karnataka reported that manual labour contributes around 50 % of total cost of turmeric cultivation (18). The increasing demand for labour and rising labour costs underscores the necessity of mechanization to reduce production costs.

Land preparation

Turmeric's intolerance to waterlogging and soil alkalinity necessitates careful consideration during land selection (19). Land preparation typically involves four passes of ploughing, using a combination of chisel and disc ploughs, followed by two passes with a cultivator (20). Raised-bed cultivation has demonstrated superior yields compared to flatbed methods, attributed to improved soil aeration, water infiltration and nutrient availability (21). Studies show that cultivating turmeric on raised beds with 60 × 20 cm spacing yields significantly heavier rhizomes (22). For instance, raised-bed cultivation produced a fresh rhizome yield of 33.55 tonnes ha^{-1}, whereas flatbed cultivation yielded only 20.97 tonnes ha^{-1} (23). Additionally, closer plant spacing improves rhizome yield per hectare due to higher plant density (24).

Planting

Turmeric is propagated using both mother and finger rhizomes, with techniques varying by region. Planting methods are broadly classified into manual, animal-driven and mechanical, based on the power source employed. Fig. 2 shows the classification of the planting methods based on power source.

Manual planting

In India, most agricultural activities, including turmeric planting, are carried out manually. Traditionally, farmers employ manual dibbling, wherein rhizomes are placed in furrows at intervals of 30 × 30 cm or 15 × 15 cm and subsequently covered with loose soil from the ridges (25). However, manual planting is inefficient, with a single labourer planting only about 0.006 ha h^{-1}. This method is also associated with poor seed placement accuracy, high labour requirements, elevated costs and physical strain on labourers (26). The timely availability of labour further determines the success of manual planting.

Women are the primary contributors to agricultural production in India, particularly in terms of value, volume and hours worked (26). In regions such as the Parbhani district of Maharashtra, traditional methods continue to dominate turmeric-related activities, including planting and earthing up (27). During the collection and sorting of rhizomes, women typically carry loads ranging from 5 to 10 kg (28). Despite its inefficiencies and associated challenges, manual planting remains widely practiced due to its accessibility and simplicity, even though it is considered the least favourable method.

Animal driven planting

Bullocks are very versatile source of power for use under various climatic conditions and undulating terrain. Bullock power reduce dependence on mechanical sources of power and reduce usage of petroleum derived fuels (29). A bullock-drawn turmeric planter was analyzed for its performance parameters (30). The planter demonstrated a missing index of 9.77 % and a multiple index of 3.15 %. The average planting depth for rhizomes was 68.5 mm, which falls within the recommended range of 40 to 100 mm for turmeric. The planter achieved crop spacing of 150 to 300 mm and row spacing of 60 mm. The effective field capacity was observed to be 0.23 ha h^{-1}, with a field efficiency of 82 %. It reduced seed rate by 20 % and overall cost by 85 % compared to manual dibbling.

Despite limited research, few animal-drawn turmeric planters are currently available. Given the widespread availability of draught animals among Indian farmers, these planters provide a viable alternative to labour-intensive manual planting, particularly for marginal farmers unable to afford mechanized equipment. However, the decreasing reliance on draught animals is evident, as their proportion in agricultural operations declined by 14.1 % between 1992 and 2009, reflecting a growing preference for mechanization

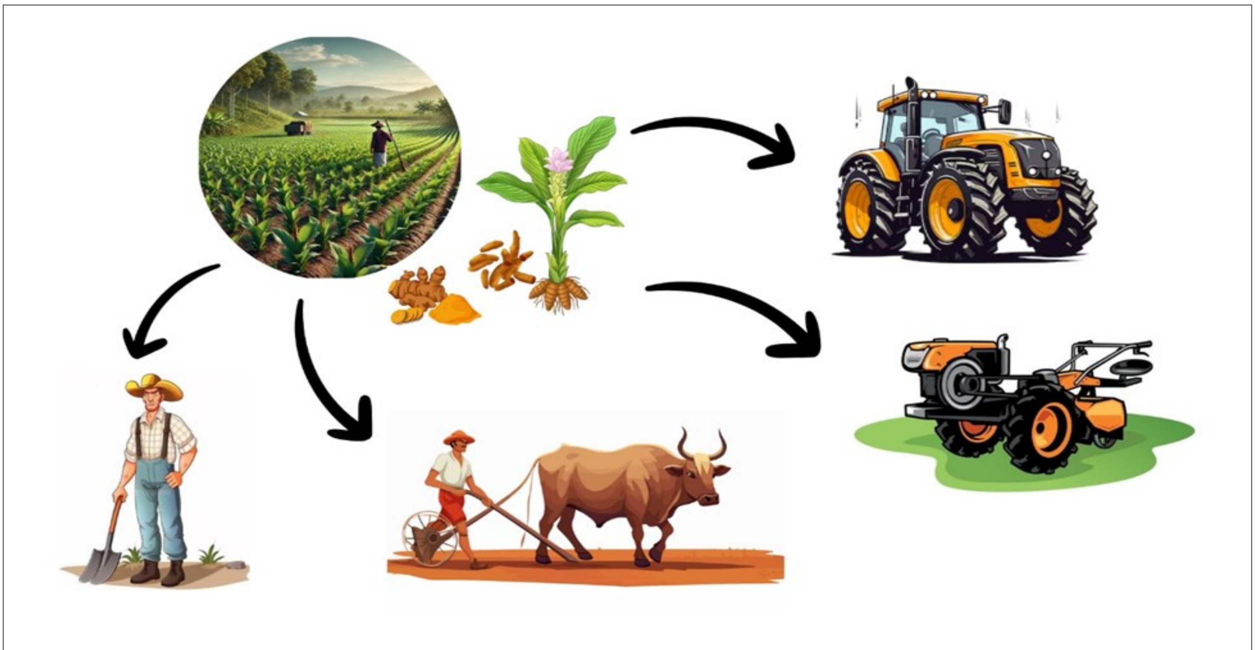

Fig. 2. Graphical representation of power sources for turmeric cultivation including human, animal, power tiller and tractor.

(31).

Mechanical planting

Agricultural mechanization has progressed rapidly, with most machinery powered by tractors. Several tractor-operated turmeric planters are available, offering improved efficiency and accuracy. For instance, a tractor-drawn turmeric planter developed by few researchers, features a metering mechanism comprising a circular disc with six grooves (70 mm × 60 mm × 50 mm) (32). The ground wheel drives the metering system through a chain and sprocket transmission. Performance tests conducted with rhizome lengths of 30 mm, 45 mm and 60 mm at operational speeds of 8 km h^{-1}, 10 km h^{-1} and 12 km h^{-1} revealed that rhizome length and operational speed had no linear relationship with the planter's missing index. The highest field capacity (0.96 ha h^{-1}) was recorded at 12 km h^{-1}, while the lowest (0.63 ha h^{-1}) occurred at 8 km h^{-1}.

Similarly, a tractor-operated turmeric planter developed by Dattkrupa Agro Engineering Works in Maharashtra, evaluated by Krishi Vigyan Kendra, exhibited field capacities of 0.085-0.10 ha h^{-1} across ten trials (33). Although the field capacity was relatively low, rhizome damage was minimal and the missing index was approximately 1 %, demonstrating high accuracy.

At Dr. Rajendra Prasad Central Agricultural University, several researchers designed a semi-automatic tractor-operated planter capable of planting two rows (20). The metering system consisted of two discs with 10 slots each, manually fed by two operators. Tests conducted at operational speeds of 0.75 km h^{-1}, 1.00 km h^{-1} and 1.25 km h^{-1} revealed an increase in rhizome spacing (220.0 mm, 222.4 mm and 230.0 mm, respectively) with speed. The missing index was highest (15.43 %) at the maximum speed of 1.25 km h^{-1}. Theoretical and effective field capacities also increased with speed, ranging from 0.067-0.112 ha h^{-1} and 0.059-0.09 ha h^{-1}, respectively.

A previous study compared the performance of two turmeric sowing machines: a tractor-drawn four-row seed drill and a two-row raised bed semi-automatic planter (34). While the four-row seed drill required four operators to feed the metering mechanism, the two-row planter required only two operators. The seed drill demonstrated superior field capacity and seed rate, outperforming the raised bed planter, as summarized in Table 2.

Mechanical turmeric planters are predominantly tractor-operated, offering superior field capacity and efficiency while ensuring timely planting. Their precision in seed placement enhances germination rates and reduces both operational costs and seed requirements per hectare. Semi-automatic tractor-operated planter further minimize human intervention in the planting process. Future research should focus on improving operational parameters and advancing automation in seed placement to enhance efficiency.

Currently, power tiller-driven planters for turmeric cultivation are unavailable. Although power tillers exhibit lower operational efficiency compared to tractors, they remain essential for small-scale farming in rural areas. Developing power tiller-operated planters would significantly benefit small and marginal farmers who cannot afford tractor-driven alternatives. Research in this direction is crucial for achieving comprehensive mechanization of turmeric cultivation.

Self-propelled planter

A self-propelled semi-automatic turmeric planter incorporating IoT-based remote control was developed (35). The system enabled real-time modification of rhizome spacing via an IoT module connected to a mobile phone. Key components included an ATmega8 microcontroller, relay, DC gear motor, motor driver L293D, IR sensor and IoT module. Although the system holds promise for enhanced precision, further field evaluation is required to assess its performance characteristics.

Harvesting

Among all operations in turmeric cultivation, harvesting is the most labour-intensive process. Root crop harvesting, including turmeric, often demands up to 600 man-hours ha^{-1} when performed manually (36). Timely harvesting is critical to maintaining both yield and quality. Turmeric is typically harvested between January and April, with early varieties maturing within 7-8 months and medium varieties requiring 8-9 months. Harvesting methods include manual techniques, animal-drawn implements and mechanical harvesters (37). Manual methods, involving hand tools such as spades and pickaxes, are labour-intensive, time-consuming and prone to damaging rhizomes, thereby reducing market value (38). Fig. 3 represent the average requirement of the different power sources for turmeric harvesting for small landholdings (39).

Understanding the physical properties of agricultural materials is integral to the development of machinery and processes for harvesting, handling and storage. Such knowledge is essential for the efficient transformation of these materials into food and feed products (40). Post-harvest studies on turmeric indicate that approximately 70 % of rhizomes are lost to spoilage and waste, primarily due to storage rot caused by improper handling and harvesting practices, which damage the rhizome's skin and flesh (41). The design and selection of harvesting methods must prioritize minimizing mechanical damage to the rhizomes. Root crop harvesting, including turmeric, differs significantly from other crops due to the need for the separation of substantial amounts of soil and foreign matter. Efficient

Table 2. Parameters obtained from field study of 4-row turmeric seed drill and 2-row raised bed turmeric semi-automatic planter (35)

Parameter	4-row turmeric seed drill	2-row raised bed turmeric semi-automatic planter
Field capacity	0.189 ha · h^{-1}	0.083 ha · h^{-1}
Field efficiency	83.72 %	79.30 %
Seed rate	1543 kg · ha^{-1}	1239 kg · ha^{-1}
Number of labours required	5	3

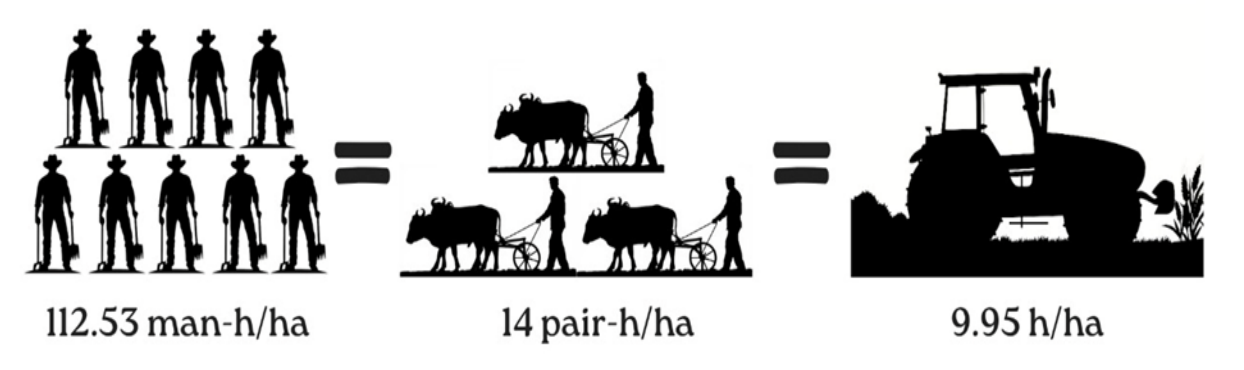

Fig. 3. Representation of field capacity of power sources for turmeric harvesting (40).

systems equipped with enhanced throughput capabilities are critical for cleaning and processing the yield (42).

Timely harvesting is crucial to minimizing post-harvest losses and extending the storage life of turmeric (43). The quality of turmeric is influenced by both, the stage of harvesting and the variety cultivated (44). Although leaving turmeric unharvested for additional growing seasons may increase physical rhizome yield, this practice negatively impacts extraction quality and increases production costs. Extraction quality deteriorates with extended maintenance, making timely harvesting essential for balancing yield and quality.

Harvesting methods for turmeric can be broadly categorized based on the primary power source into four types: manual, animal-drawn, power tiller-operated and tractor-operated. Each method and its application are discussed in detail in subsequent sections.

Manual harvesting

Farmers primarily utilize simple hand tools, such as spades and pickaxes, for soil excavation (37). The traditional method of harvesting turmeric involves irrigating the crop after the removal of foliage, followed by manual extraction of rhizomes using specialized fork-like spades after a one-week interval. Manual harvesting frequently causes bruising and physical damage to rhizomes, adversely affecting their overall quality and economic returns (38).

The researchers observed that human labour accounts for more than 44 % of the total processing costs in turmeric production (45). Hand harvesting of root crops requires two to eight times more labour hours than other farming activities (46). A previous study reported that manual turmeric harvesting achieves an operational efficiency of 90.5 % but results in approximately 7.10 % rhizome damage (47). This method is labour-intensive, time-consuming and accounts for 30-40 % of the total production costs. Labor requirements for harvesting turmeric are estimated at 40 man-days per hectare for male workers and 100 man-days per hectare for female workers (48).

Animal drawn harvesting

The use of draught animals remains a common practice for turmeric harvesting in India due to their widespread availability among farmers. Bullock-operated wooden ploughs are traditionally employed to extract rhizomes (38). In addition to conventional ploughs, specialized animal-drawn harvesters designed specifically for turmeric have been developed to enhance operational efficiency while minimizing rhizome damage.

A prototype bullock-drawn turmeric digger, designed by Marathwada Agricultural University in Parbhani, Maharashtra, was developed and evaluated for cultivars grown in the Parbhani and Nanded districts of the state. The researchers conducted a performance analysis of this digger, focusing on the optimization of blade parameters (49). The digger, operated by a pair of bullocks with a draft capacity of 0.8 hp, was tested using three blade types: a V-blade with angles of 70° and 120° and a semi-circular blade. Field trials indicated a draft requirement of 98-109.5 kgf, with an operational speed of 1-1.5 km h^{-1}. The depth of operation ranged from 190-235 mm, aided by the addition of a 50 kg sandbag as dead weight. Considering the optimum rhizome depth of 200 mm, the digger exhibited acceptable performance. Among the blades tested, the 70° V-blade demonstrated superior field and digging efficiency, with minimal rates of undug and damaged rhizomes, whereas the 120° blade showed comparatively poorer performance. Detailed performance results for each blade type are presented in Table 3.

Table 3. Performance parameters of different blades from field trials (50)

Parameter	70 ° blade	120 ° blade	Semi-circular blade
Field efficiency (%)	89	74	88
Digging efficiency (%)	94	86	91
Rhizomes undug (%)	7.69	13.96	8.23
Damage percentage (%)	10.72	19.62	15.46

A bullock-drawn digger for turmeric and ginger was later developed, as illustrated in Fig. 4 (50). This digger consisted of a frame, blade, beam, shank, handle, sweep and wheels and was specifically designed for use with Red Kandhari bullocks, a breed native to Maharashtra, India. The operational width of the digger was set at 600 mm, with two sweeps weighing 65 kg. The digger was subjected to three trials each for turmeric and ginger and its performance metrics are summarized in Table 4.

A comparative evaluation of the bullock-drawn turmeric digger with a 70° blade and the turmeric and ginger digger developed by few researchers revealed notable differences in their performance (49, 50). While the digger by previous study demonstrated superior field and digging efficiency, it caused greater rhizome damage

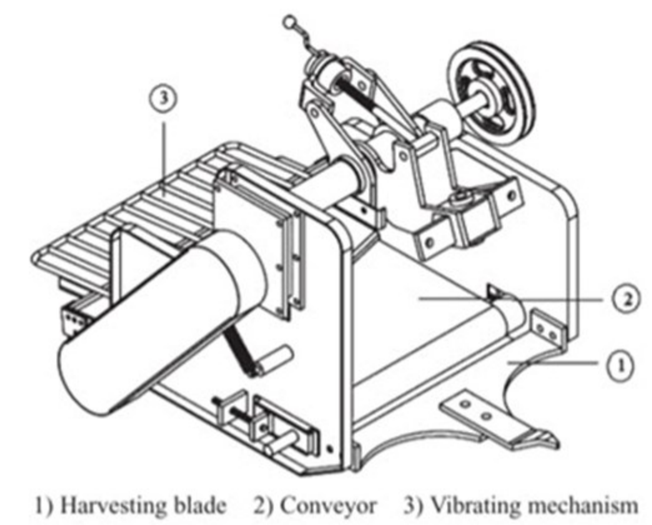

Fig. 4. Bullock Drawn turmeric and ginger digger (50).

Table 4. Performance parameters of bullock drawn ginger and turmeric digger (51)

Parameter	Turmeric	Ginger
Depth of operation (mm)	180	178
Digging efficiency (%)	92.74	91.03
Damage Percentage (%)	7.65	8.93
Average draft requirement (kg)	85.33	85.66
Average actual field capacity (ha·h$^{-1)}$	0.18	0.18
Field efficiency (%)	83.16	85

Table 5. Comparison of performance parameters bullock drawn turmeric digger and ginger digger

Parameter	Munde et al. (2010)	Zate et.al. (2018)
Field efficiency (%)	89	83.16
Digging efficiency (%)	94	92.74
Damage percentage (%)	10.72	7.65

(10.72 %) compared to the digger developed by another study, which exhibited lower damage rates (49, 50). The performance parameters are given in Table 5.

Mechanical harvesting

Mechanical harvesters, such as power tiller-operated and tractor-mounted diggers, are becoming increasingly popular among turmeric farmers due to their efficiency and ability to address key labour challenges (37). The limited availability of skilled labour and rising labour costs necessitate the adoption of mechanized harvesting methods. These machines are designed to extract rhizomes with minimal damage to their delicate structure, thereby improving overall yield and reducing the dependency on labour-intensive manual harvesting practices (51). Furthermore, the adoption of mechanized solutions increases with the expansion of farm size, demonstrating the scalability of such technologies (39).

Power tiller operated harvesting: Power tiller-operated turmeric diggers hold significant potential for improving harvesting efficiency, especially among small-scale farmers, who are often equipped with power tillers (48). Recent technological advancements have enabled the development of efficient turmeric harvesters compatible with power tillers.

One such harvester, powered by a 9 kW power tiller, consists of two primary functional components: a harvesting blade and a conveyor system with a vibrating mechanism (48). The chisel blade, measuring 900 × 200 × 10 mm, is mounted at the front and excavates rhizomes along with soil. The conveyor system collects the excavated material and a vibratory mechanism separates a portion of the soil from the rhizomes. The cleaned rhizomes are then discharged at the rear of the harvester and manually collected. Field evaluations revealed a 6.5 % increase in digging efficiency using this harvester. However, the conveyor system deposits the harvested rhizomes on the ground, necessitating manual collection, which increases labour requirements. Specifically, the labour demand for this power tiller-operated harvester is 2.5 man-hours ha^{-1} for operation and 80 woman-hours ha^{-1} for manual collection of rhizomes from the field (48).

Tractor operated harvesting: The researchers developed a tractor-operated turmeric harvester powered by a 35-hp tractor (47). This prototype features a single harvesting blade designed to uproot alternate rows of turmeric. The blade, mounted on a mild steel channel box frame, is driven by a gearbox connected to the tractor's power take-off (PTO). The 900 mm wide digging blade at the front excavates the rhizomes, which are transported via a conveyor belt to an oscillating box at the rear. The oscillating mechanism separates the soil from the rhizomes, which are then collected. Field tests conducted on the Erode variety of turmeric grown in clay loam soil at a forward speed of 2.5 km h^{-1} yielded promising results. Performance parameters are detailed in Table 6.

Table 6. Performance parameters of the prototype harvester (48)

Parameter	Value
Blade angle (degree)	20
Conveyor dimension (mm)	1060 × 1520
Conveyor belt	Rubber strips
Effective field capacity (ha·h$^{-1)}$	0.16
Harvesting efficiency (%)	98.5
Damage percentage (%)	2.3

Previous research developed another root crop harvester, powered by an 18-24 hp tractor using a three-point linkage system (52). This harvester includes a soil-cutting blade angled at 25° to the horizontal, capable of cutting to a depth of 180-200 mm with an effective working width of 600 mm. The harvested soil mass and rhizomes are lifted to webs positioned at a 100° inclination to the blade. As the loosened material passes through the webs, the soil is separated, leaving the rhizomes to be manually collected. Field testing at an operational speed of 2 km h^{-1} demonstrated an effective field capacity of 0.129 ha h^{-1}, a field efficiency of 80.57 % and a fuel consumption rate of 1.86 l h^{-1}. The harvester achieved a digging efficiency of 98.82 % and a rhizome damage rate of 1.32 %. Compared to manual harvesting, the use of this harvester reduced total operating costs by 33.21 %.

A tractor PTO-operated turmeric digger-cum-separator was developed by few researchers (37). The primary components of the machine included a digging unit, elevator conveyor system, gearbox housing, ground wheel and power transmission system, all mounted on a main frame measuring 1610 × 1140 mm. Power from the tractor's PTO was transmitted to a gearbox, which supplied power to the elevator conveyor system via a belt drive. Two-gauge wheels with a diameter of 450 mm were positioned 1200 mm apart for stability, while two pneumatic wheels (320 mm in diameter) supported the sides. Following the blade, a flat surface facilitated soil displacement from the dug crop. The soil-separation unit, constructed from mild steel rods with 30mm spacing, measured 1500 × 1080 mm. The optimized blade geometry, angled at 20° to the horizontal, ensured efficient performance. The digger achieved a field capacity of 0.47

Fig. 5. Tractor PTO-operated turmeric digger-cum-separator in field (38).

ha h^{-1} with a digging efficiency of 97.35 %, a soil separation index of 0.24 % and rhizome damage of 3.34 %. The depth of cut was 215 mm, with fuel consumption of 6.12 l h^{-1}, power requirements of 0.91 kW and a draft force of 2.199 kN. The field operation of the harvester is shown in Fig. 5.

A mini-tractor-operated turmeric harvester was developed for small-scale farmers by Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu (Fig. 6)

Fig. 6. Mini tractor operated turmeric harvester (55).

(53). Its construction comprised a rectangular main frame (300 × 1000 × 600 mm), a conveyor support frame (700 × 1000 × 600 mm), a power transmission system, a digging blade and a conveyor mechanism. The harvester was powered by the tractor's PTO shaft, which transmitted power via a gearbox and a belt-and-pulley system to the conveyor. The digging system featured a straight blade with a digging chisel (100 × 20 × 8 mm) and a guiding rake, while the conveyor (70 × 1000 mm) facilitated soil separation from the dug rhizomes.

The researchers developed a turmeric harvesting machine designed for operation by 15-20 kW mini tractors with PTO speeds of 540 rpm (54). Its frame, constructed from C-beams and hollow members, measured 1260 mm in length with an operational width of 600 mm. The blade's approach angle ranged from 10° to 20°. The machine operated at speeds of 300-400 rpm. Preliminary laboratory trials evaluated soil segregation using a DC motor attached to the apparatus; however, no field trials were conducted to validate its performance.

A semi-automatic harvesting machine incorporating an elevator conveyor system and windrower was designed and evaluated (55). The digging blade (1000 × 200 × 10 mm) was positioned at a 20° angle to the horizontal, supported by two-gauge wheels (450 mm in diameter and 1200 mm apart). A vibration unit located behind the digging blade facilitated soil loosening. The vibrator rod, measuring 1180 mm in length and 40 mm in diameter, was driven by the tractor's PTO shaft via a gearbox. Pneumatic wheels (320 × 100 mm) were mounted at the centre on both sides of the harvester for added stability. The elevator conveyor, composed of mild steel rods spaced 30 mm apart, measured 1115 × 1100 mm and was positioned behind the vibration unit to enable soil-rhizome separation. Field testing for ginger harvesting at a forward speed of 2.5 km h^{-1} yielded a theoretical field capacity of 0.22 ha h^{-1}, an effective field capacity of 0.18 ha h^{-1} and a field efficiency of 81.8 %. Additional performance metrics included a digging efficiency of 99.18 %, rhizome damage of 1.06 %, a separation index of 85.38 % and a conveying efficiency of 99.72 %.

Field trials for the PAU model tractor-operated root crop harvester, developed by Punjab Agricultural University, Punjab were conducted across 11 trials (Fig. 7). It covered 6.40 ha of potato and ginger fields at seven locations in

Fig. 7. Tractor drawn root crop harvester for potato and ginger crop (58).

Jabalpur, Madhya Pradesh (56). The machine demonstrated a digging efficiency of 95 % for potatoes and 93 % for ginger, with actual field capacities of 0.21 ha h^{-1} and 0.18 ha h^{-1}, respectively. Field efficiency was recorded at 68 % for potatoes and 64 % for ginger. Cost savings compared to manual harvesting were significant, amounting to 85.64 % for potatoes and 83.35 % for ginger. Further optimization of the machine's operating parameters is required to adapt it for other root crops such as turmeric, carrots, onions, garlic and sweet potatoes.

Previous researchers designed a versatile harvesting machine for root crops comprised a digger, screener and power transmission system (57). Powered by a 2-stroke petrol-fuelled chainsaw engine operating at 9000 rpm, the machine featured a six-legged structure with wheels attached to each leg. A solid shaft fitted with multiple blades was mounted on one side of the chassis and rotated via a drive shaft to penetrate and loosen the soil, enabling root crop extraction.

A ginger harvester powered by an engine was developed by few researchers (58). The engine's output shaft transmitted power through a chain drive to a rotary shaft. The machine's speed was increased from 20 rpm to 25 rpm using sprockets with 11 and 44 teeth. Soil was separated from the ginger by screener blades, ensuring minimal damage to the crop, which was subsequently collected manually.

Turmeric harvesters powered by bullocks, power tillers and tractors have been evaluated for their efficiency (Table 7). As previously discussed, although bullock- and power tiller-operated harvesters are less efficient, they remain most viable options for small-scale rural farmers who cannot afford tractor-driven alternatives. One of the primary challenges in turmeric harvesting is the separation of soil from the rhizomes due to the complex clump structure. Therefore, specialized mechanisms are required to facilitate soil loosening and improve the cleaning process. Vibratory mechanisms, conveyors and elevators are commonly employed to disintegrate the soil-rhizome mass. However, even after undergoing these processes, soil particles often remain adhered to the rhizomes.

A tractor-drawn turmeric digger-cum-separator has demonstrated superior cleaning efficiency (37). Nevertheless, fine-tuning and optimization of the cleaning system are essential to enhance effectiveness while minimizing rhizome damage. Furthermore, all existing harvesters leave the harvested rhizomes in the field, necessitating additional labour for manual collection. Integrating an automated collection system into the harvester could eliminate this labour-intensive process, thereby improving overall harvesting efficiency.

Future Prospects

Studies among turmeric cultivators in Andhra Pradesh and Karnataka highlight critical challenges, with over 96 % struggling with labour shortages and rising wages (59). Moreover, a significant portion remains unaware of advanced farming techniques and is resistant to adopting new technologies (60). The most effective solutions involve introducing advanced machinery and conducting extensive outreach programs to enhance farmers' technological awareness and adoption rates. Government investment in R&D, skill development and policy frameworks will accelerate mechanization. Collaboration between research institutions and the private sector will further drive innovation.

However, the substantial initial investment required for machinery remains a major constraint, discouraging many local farmers from adopting mechanized solutions. The adoption of turmeric machinery can be accelerated through subsidies provided under schemes like the Sub-Mission on Agricultural Mechanization (SMAM). These subsidies benefit not only individual farmers but also custom hiring centres and farmer producer organizations. However, to achieve widespread mechanization, a coordinated strategy must be implemented, ensuring seamless collaboration from the ministry level down to the farmers. Recognizing the potential of the turmeric industry, the Government of India has established the Turmeric Board to implement strategic initiatives, including full-scale mechanization, to enhance productivity and sustainability (61).

India accounts for the majority of global turmeric production, with China, Myanmar and Nigeria also playing significant roles. As a frontrunner in the industry, India has the potential to lead the mechanization movement in turmeric cultivation. The development of globally standardized machinery incorporating modern technologies will not only enhance domestic productivity but also create opportunities for technology transfer and machinery exports, strengthening India's position in the international agricultural machinery market.

Conclusion

India is the world's largest producer of turmeric. However, the Indian turmeric industry remains underdeveloped in

Table 7. Performance factors of different harvesters for turmeric

Author	Description of machine	Field capacity (ha·h^{-1})	Field efficiency (%)	Harvesting efficiency (%)	Damage percentage (%)
Annamalai & Udayakumar (2007)	Tractor operated digger cum elevator turmeric harvester	0.16	-	98.5	2.3
Khambalkar et al. (2019)	Tractor operated turmeric harvester with webs to remove soil	0.129	80.57	98.82	1.32
Deshvena et al. (2019)	Tractor drawn turmeric digger cum separator	0.47	-	97.35	3.34
Thilak et al. (2021)	Semi-automatic root vegetables harvesting machine	0.18	81.8	99.18	1.06
Narender, 2022)	Harvester for turmeric and ginger	0.133	87.82	97.76	3.30

terms of mechanization, particularly in the adoption of advanced machinery for cultivation. This study explored the technological advancements employed in turmeric farming. Commonly, land preparation is done by tillage implements include the mouldboard plough and cultivator. To ensure optimal work quality, it is imperative to optimize machine parameters (62). Developing implements specifically designed for turmeric cultivation could significantly enhance production rates and overall efficiency. Performance parameters, advantages and disadvantages of turmeric planters and harvesters are analyzed (Table 8). Studies on turmeric planters have produced conflicting results. For instance, the field capacity of a bullock-drawn planter was recorded at 0.23 ha h^{-1}, which surpasses that of some mechanical planters (30). However, one tractor-drawn planter (32) exhibited an anomalous field capacity of 0.96 ha h^{-1}, in contrast to the average field capacity of other tractor-drawn planters, which was only 0.115 ha h^{-1} (20). These inconsistencies make it challenging to recommend an optimal planter based on available data. Nevertheless, a 4-row turmeric seed drill, with a recorded field capacity of 0.189 ha h^{-1} and a field efficiency of 83.72 %, appears to be a promising option for efficient planting operations (34). Existing turmeric harvesters primarily dig up rhizomes and leave them on the ground. Some advanced models incorporate conveyors and elevators to separate soil clods before depositing the rhizomes in the field. While this method aids soil removal, it necessitates additional labour for rhizome collection, increasing operational costs and impacting economic viability. Recent studies indicate that a turmeric harvester with a chain conveyor for soil separation enhances cleaning efficiency and minimizes rhizome damage (37). To optimize turmeric harvesting and improve cost-effectiveness, the development of an integrated harvesting and collection system is crucial. To enhance the efficiency and economic viability of turmeric farming, future research should focus on the complete automation of the cultivation process. The development of automatic planters and advanced harvesters equipped with cleaning and collection units can significantly reduce labour dependency and operational costs. Additionally, targeted extension programs and supportive government policies will be instrumental in elevating the mechanization levels of turmeric cultivation, ensuring sustainable growth in the sector.

Acknowledgements

We acknowledge Tamil Nadu Agricultural University for the support and guidance given while writing this article.

Authors' contributions

BY collected the relevant literature on the topic. BY and PD wrote the article from the collected literature and

Table 8. Advantages and disadvantages of significant planters and harvesters

Machinery	Advantage	Disadvantage
	Planter:	
Bullock-drawn turmeric planter (30)	Reduced seed rate by 20 % and overall cost by 85 % compared to manual dibbling. Optimum planting depth achieved.	When compared to mechanical harvesters the efficiency is low.
Tractor-drawn turmeric planter (32)	Improved efficiency and accuracy.	-
Semi-automatic tractor-operated planter (20)	Require minimum human interaction for seed metering.	Further developments are needed for increasing field capacity.
4-row turmeric seed drill (34)	Cover four rows in single pass.	Total five operators are necessary.
2-row raised bed turmeric semi- automatic planter (34)	Only three operators are needed.	Lower field capacity and increased seed rate.
	Harvester:	
Bullock-drawn turmeric digger (49)	Suitable for small scale farmers. Comparable performance efficiency.	Collection and cleaning of rhizomes are done manually. Higher undug and damaged rhizomes quantity.
Power tiller operated turmeric harvester (48)	A vibratory mechanism for cleaning of rhizomes. Increased digging efficiency. Reduced labour requirement than manual and animal harvesting.	Rhizomes collected manually from the field.
Tractor-operated turmeric harvester (47)	Conveyor belt and oscillatory mechanism attached for soil separation.	Manual post digging ground collection.
Root crop harvester (52)	Webs are provided to loosen and separate the soil.	Cleaning of rhizomes is not effective. Further involvement of labour needed for collecting the rhizomes.
Tractor drawn turmeric digger cum separator (37)	Elevator conveyor is attached to ensure effective soil separation. Higher field capacity and separation index.	No provision for storing the clean rhizomes. Deliver them to field, requiring manual collection.
Mini-tractor-operated turmeric harvester (53)	Suitable for small land holdings. A conveyor provided for soil separation.	Soil separation is inefficient.
Semi-automatic root vegetable harvester (55)	Elevator conveyor system and windrower incorporated.	Low field capacity.
PAU model tractor-operated root crop harvester (56)	Suitable for ginger and potato	Not designed specifically for turmeric.

evaluated them critically. RK, AS and GA supervised the process and edited the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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