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Akash T Pawar
Dr. Balasaheb Sawant Konkan
Krishi Vidyapeeth, Dapoli,
Maharashtra, India

VK Tiwari
Junagadh Agricultural University,
Junagadh, Gujrat, India

Vasu Kumar
Dr. Balasaheb Sawant Konkan
Krishi Vidyapeeth, Dapoli,
Maharashtra, India

Mahesh D Nikam
Dr. Balasaheb Sawant Konkan
Krishi Vidyapeeth, Dapoli,
Maharashtra, India

Development and evaluation of a rotavator-powered integrated system for mechanized plastic mulch application

Akash T Pawar, VK Tiwari, Vasu Kumar and Mahesh D Nikam

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Abstract

Plastic mulching is an effective agronomic practice for conserving soil moisture, suppressing weeds, and improving crop productivity; however, its adoption is constrained by labour-intensive installation and the limited availability of affordable mechanized systems. To address these challenges, a rotavator-powered integrated plastic mulch application system was developed to perform rotary tillage, bund formation, drip lateral placement, and plastic mulch laying in a single pass. The developed machine was evaluated under field conditions to assess its technical and economic performance. The machine operated satisfactorily, producing uniform bunds and laying the plastic mulch sheet without tearing. It achieved an average effective field capacity of 0.133 ha/h, field efficiency of 70.59%, and fuel consumption of 4.13 l/h. Numerical optimization identified an optimum forward speed of 1.75 km/h, providing the best compromise between field capacity, field efficiency, and fuel consumption. The operating cost of the machine was estimated at ₹5771.40 per hectare, with a payback period of 5.87 years. The developed machine offers a technically feasible and economically viable solution for mechanized plastic mulch application by integrating multiple field operations into a single pass, thereby reducing labour requirements, field time, and overall production costs.

Keywords: Conservation tillage, drip laying, plasticulture, seedbed preparation, soil–mulch interaction.

Introduction

Agriculture remains a cornerstone of the Indian economy, providing livelihood to approximately 46.1% of the population and contributing about 17.94% to the national Gross Domestic Product (GDP) during 2024–2025, according to the Press Information Bureau (PIB) and the National Statistical Office (NSO). Traditionally, agricultural production was largely dependent on natural resources and manual labour. However, the increasing demand for food, fibre, and bio-based products, coupled with shrinking natural resources and climate variability, has intensified the need for resource-efficient and sustainable production systems. Consequently, the adoption of advanced agronomic practices and modern technologies has become essential for enhancing crop productivity, improving input-use efficiency, and maintaining competitiveness in agricultural markets. Among these technologies, plastic mulching has emerged as an effective crop management practice owing to its potential to conserve soil moisture, regulate soil temperature, suppress weed growth, and improve crop yield and quality.

Mulching is the common practice of putting materials, such as plastic sheets, crop residue, livestock manure, sands, rocks, and cement, to the field before, during, or shortly after the sowing over the soil surface (Gan *et al.*, 2008) [5]. Mulching increases yield and quality of produce, controls temperature, reduces weeds, and preserves soil moisture (Khose *et al.*, 2023; Demu and Bogale, 2024) [9, 3]. Additionally, it also contributes to reduce surface runoff, enhance infiltration, and act as an evapotranspiration barrier (Rathore *et al.*, 1998; Zhou *et al.*, 2011; El-Beltagi *et al.*, 2022) [18, 25, 4]. Traditionally, organic mulches such as straw, leaves, and compost have been extensively used; however, their use is often constrained by several drawbacks. These include the risk of weed seed contamination, excessive soil warming that may delay crop emergence and fruit ripening in warm-season vegetables, and the potential to infestation of pests (Hill *et al.*, 1982; Patil *et al.*, 2013) [7, 16].

Corresponding Author:
Akash T Pawar
Dr. Balasaheb Sawant Konkan
Krishi Vidyapeeth, Dapoli,
Maharashtra, India

In particular, straw mulch can introduce weed seeds into the soil and, due to its high C/N ratio, may cause temporary nitrogen immobilization during decomposition, thereby depleting seedbed nitrogen availability (Li *et al.*, 2021; Yu *et al.*, 2020) ^[13, 24].

Over the last five to six decades, synthetic or plastic mulches have gradually replaced traditional organic materials, offering several advantages such as enhanced soil temperature regulation, improved moisture conservation, and effective suppression of pests and weeds (Kasirajan and Ngouajio, 2012; Subrahmaniyan *et al.*, 2018; Choudhari *et al.*, 2020) ^[8, 20, 1], and enhanced productivity in crops like tomato (*Lycopersicon esculentum* Mill.), chili peppers (*Capsicum frutescens* L.), Cauliflower (*B. oleracea* L. var. *Botrytis*), Cabbage (*Brassica oleracea* L. var. *Capitata*) (Clarkson and Frazier, 1957) ^[2]. Recent studies have highlighted their role in reducing soil compaction, improving germination, and increasing nutrient-use efficiency (Gowd and Prasad, 2017; Kumar *et al.*, 2014) ^[6, 11].

Despite these advantages, the large-scale adoption of plastic mulching in India remains limited, due to the reliance on manual or animal-aided methods for laying mulch films. Such practices are often time-consuming, labour-intensive, and inefficient, leading to issues such as sheet tearing, inadequate edge coverage, and reduced field efficiency (Pathak *et al.*, 2022) ^[15]. Although bullock-drawn and tractor-operated mulch-laying devices have been developed and tested with promising results, their application is still limited due to high labour requirements, limited availability, high costs, and inadequate operational efficiency (Marihonnappanavara *et al.*, 2017; Kothiya *et al.*, 2021; Lham *et al.*, 2024) ^[14, 10, 12].

This technological gap underscores the need for an efficient mechanized system capable of integrating plastic mulch application with routine field operations. Considering the widespread use of tractor-operated rotavators for seedbed preparation, integrating a mulch-laying attachment with the rotavator to simultaneously perform seedbed preparation, drip lateral placement, and plastic mulch laying in a single pass represents a promising approach. Such an integrated system can improve field operational efficiency by reducing the number of field passes, optimizing tractor power utilization, lowering labour and operational costs, and ensuring uniform placement of drip laterals and plastic mulch, thereby enhancing the overall quality and timeliness of field preparation.

Materials and Methods

The study was conducted at the Department of Farm Machinery and Power Engineering, College of Agricultural Engineering and Technology, Junagadh Agricultural University. The developed machine comprised a tractor-operated rotavator integrated with a bund-forming unit, a plastic mulch-laying and soil-covering unit, and a drip lateral placement unit, enabling multiple field operations to be performed in a single pass.

Functional and Design Requirement

Functional and design requirements are the fundamentals for better performance of the machine and execution of its intended function under actual conditions. The functional requirements for the machine to work effectively were compiled as follows:

- The machine must be able to perform soil pulverization, drip lateral laying, and mulch laying simultaneously while constructing a single bed of 75-90 cm wide.
- It must be compatible with existing rotavators and utilize tractor PTO and drawbar power for effective operation.

- The design must emphasize simplicity, employ locally available materials, and allow for easy installation, dismantling, inspection, and maintenance.
- The machine shall ensure operational convenience, quick attachment/detachment, and minimum fabrication as well as operating costs.

Development of Combination Mulching Machine

The proposed machine was developed at CAET Junagadh, the machine is suitable for laying mulch sheet of up to 1 m width. The mulching machine consists of various parts like main frame, bund forming unit, drip laying unit, mulch laying unit and mulch sheet covering unit. Description of different components is given in following sections:

Main Frame

The main frame was made of a rectangular mild steel frame (40 × 40 × 2 mm) with overall dimensions of 1300 × 830 mm. The frame was attached to the rotavator using bolts, and major components including the press wheel, mulch-laying unit, and soil-covering unit were mounted on the frame through holders with nut-bolt connections.

Plastic Mulch Laying Unit

The mulch roll carrier was mounted on the main frame using two pillow block bearings (P205), positioned 400 mm from the front end and fixed with nut-bolt connections. A 1250 mm cylindrical pipe was supported between the bearings to hold the mulch roll, with flanges provided at both ends to prevent lateral displacement

Drip Laying Unit

A roller of 100 mm diameter and 600 mm width was used to hold drip irrigation pipes. Four pairs of 400 mm long mild steel flats (20 × 3 mm) were welded at its edges to secure the laterals. The roller was mounted on a 650 mm long, 25 mm diameter circular pipe, which was fixed to the rotavator.

Bund Making Unit

The bund former unit, attached to the rear end of the rotavator, was designed to form bunds of 750–900 mm width by collecting soil from the front and converging it into a compact shape at the rear. It was fabricated from 4 mm mild steel sheet (350 mm length, 280 mm height), with a front opening width of 1230 mm tapering to 750 mm at the rear.

Press Wheel

A pair of solid rubber press wheels (200 mm diameter, 50 mm width) was mounted behind the mulch-laying unit to press the edges of the plastic film onto the soil. The wheels were fixed to the main frame through clamps, with holders fabricated from 60 × 30 mm MS flats and 350 mm long 40 × 40 mm MS square pipes, secured using nut-bolt assemblies.

Soil Covering Unit

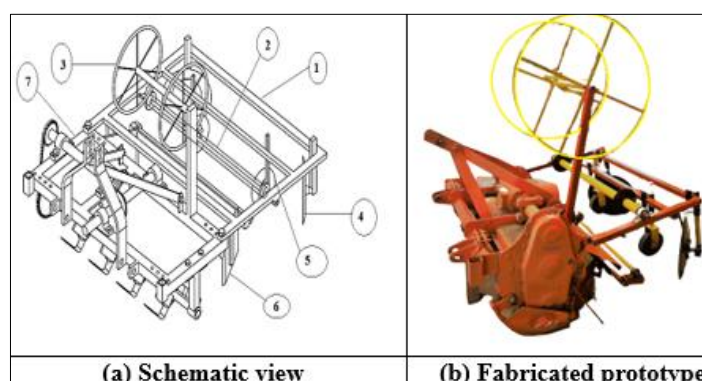
The soil-covering unit consisted of two concave circular discs, each positioned at a 45° angle to the direction of travel behind the press wheels, to cover the laid plastic mulch with soil. The discs measured 450 mm in diameter and 3 mm in thickness, with additional 150 mm diameter, 6 mm thick supporting discs bolted to enhance rigidity and prevent deflection or bending. The details of the developed mulching machine are given in Table 1.

Table 1: Specifications of developed mulching machine

Particular	Details
Overall dimensions of machine (L x W) mm	1300 x 830
Power source	John deere 5050 E Tractor (50 hp)
Bund making unit dimensions (L x W x T) mm	350 x 280 x 4 mm
Covering disc type, material and size	Two concave covering disc of 450 mm diameter
Press wheel type and diameter	2 Solid rubber wheel, 200 mm diameter
Drip laying unit	100 mm diameter and 600 mm width

Developed Machine and Its Working Principle

The proposed machine prepares a field by tilling, pulverizing, and levelling the field with the help of rotavator and forms a soil bund using the bund former. Simultaneously, the machine lays the drip lateral and the plastic mulch sheet over the prepared soil bund. Both the edges of the plastic sheet as a mulch are covered by the soil using soil covering discs. Thus, all the three operations are completed in a single pass. The schematic and isometric view of the developed machine are shown in Fig. 1.

**Fig 1:** Developed combined mulching machine

- 1) Main frame,
- 2) Mulch Laying unit,
- 3) Drip lateral laying unit,
- 4) Soil covering unit,
- 5) Press wheels,
- 6) Bund forming units,
- 7) Rotavator

Field Performance Evaluation of Developed Combined Mulching Machine

The machine was evaluated at three speeds of operations were taken as low (1.0–1.5 km/h), medium (1.5–2.0 km/h), and high (2.0–2.5 km/h). The developed machine was evaluated for mulching operation and various performance field capacity parameters.

Descriptions of different parameters are given in following sections:

Width and Height of Bund Formed

The width and height of bund formed by the bund making unit attached at the rear side of rotavator was measured by measuring tape and depth gauge by measuring the horizontal distance between two edges of bund formed and the distance between surface of soil and upper edge of bund respectively.

Wheel Slip

Percentage of wheel slip is also called travel reduction ratio. However, the travelled distance of tractor in a given number of revolutions increases in a few cases when the mounted implement pushes the tractor as in case of rotavator. Thus, the wheel slip is

negative. Coloured mark was made on the rear wheel such that it was easily observed during forward movement of the tractor. The distance covered in ten-wheel revolutions was recorded with and without load and the values were used to calculate slip using following expression (Prem *et al.*, 2017) ^[17].

$$S = \frac{D_1 - D_2}{D_1} \times 100$$

Where,

S = Slip (%),

D₁ = Distance covered in 10 revolutions of drive wheel at no load in field (m),

D₂ = Distance covered in 10 revolutions of drive wheel at load in field (m).

Fuel Consumption

The fuel consumption of tractor was measured as per the standard prescribed method (Thakare, 2009) ^[21]. The auxiliary tank/jar (Fuel meter) was attached on tractor in between fuel tank and engine. The time of operation by tractor and fuel consumed in auxiliary tank were recorded. Fuel consumption of tractor was determined by dividing the fuel consumed to the time of operation.

Fuel consumption (l/h)=

$$\frac{\text{Difference in level of tank before and after operation (l)}}{\text{Time taken to cover the targeted area (h)}}$$

Mulch Sheet Covering Percentage

The length of mulch sheet which was covered and uncovered by soil was measured with the help of measuring tape and mulch sheet covering efficiency was calculated.

Determination of Machine Performance Parameters

Theoretical Field Capacity

Theoretical field capacity (TFC) is the rate of area covered without loss of time. It was calculated by using following formula.

$$\text{TFC} \left(\frac{\text{ha}}{\text{h}} \right) = \frac{\text{Width of coverage (m)} \times \text{Speed} \left(\frac{\text{km}}{\text{h}} \right)}{10}$$

Effective Field Capacity

Effective field capacity (EFC) is the actual rate of work which includes the time lost in turning at the end of rows and time lost during changing of mulch roll. It was calculated by using following formula.

$$\text{EFC} \left(\frac{\text{ha}}{\text{h}} \right) = \frac{\text{Width of coverage (m)} \times \text{Length of strip (m)}}{\text{Time taken (h)} \times 10,000}$$

Field Efficiency

Field efficiency (FE) is defined as the percentage of time the machine operates at its full rated speed and width while in the field. It was calculated by using following formula.

$$FE (\%) = \frac{\text{Effective field capacity}}{\text{Theoretical field capacity}} \times 100$$

Cost of Operation

The operation cost was analysed for the developed machine. Depreciation cost was calculated based on straight-line method.

Results and Discussion

Speed of operation

As per the experimental design, machine was evaluated at three different forward speeds of tractor as 1.0-1.5, 1.5-2.0 and 2.0-2.5 km/h respectively. The average speed of operation during operation was found 1.23, 1.52 and 2.1 km/h.

Width and height of bund formed

The width and height of bund formed were measured at different locations with the help of measuring tape and depth gauge. The average width and height of the bund formed by the developed tractor operated bund former was 84 cm and 20.6 cm respectively.

Wheel slip

The observations for the wheel slip were measured at speed of 1.0-1.5 km/h, 1.5-2.0 km/h and 2.0-2.5 km/h resp. The obtained wheel slip was -1.75, -2.22 and -2.43% resp. The negative wheel slip was attributed to the thrust generated by the PTO-driven mounted rotavator, which exerted a forward pushing force on the tractor, resulting in an apparent reduction in wheel slip.

Theoretical Field Capacity

The theoretical field capacities of the developed mulching machine were found 0.13, 0.195 and 0.26 ha/h at 1.0-1.5, 1.5-2.0 and 2.0-2.5 km/h speeds respectively. The results showed that effective field capacity of the developed machine increased with increasing speed of operation.

Effective Field Capacity

During the operation the average effective field capacity calculated at 1.0-1.5 km/h, 1.5-2.0 km/h and 2.0-2.5 km/h speeds

were 0.1080, 0.1314 and 0.1595 ha/h respectively. The increase in effective field capacity can be attributed to the higher travel speed, which enabled greater field coverage per unit time. Similar trends have been reported for tractor-operated tillage and planting implements, where effective field capacity is primarily governed by forward speed under constant implement width and operating conditions.

Field Efficiency

The average field efficiency of the developed machine was 83.07%, 67.50%, and 61.21% at forward speed ranges of 1.0–1.5, 1.5–2.0, and 2.0–2.5 km/h, respectively. Forward speed had a highly significant ($p < 0.01$) effect on field efficiency, which decreased with increasing speed. The decline in field efficiency may be attributed to increased operational losses and reduced precision at higher operating speeds. Although the effective field capacity increased due to greater area coverage per unit time, the corresponding increase in theoretical field capacity was proportionally higher, resulting in a decline in field efficiency.

Fuel Consumption

The average fuel consumption of the developed machine at forward speed ranges of 1.0–1.5, 1.5–2.0, and 2.0–2.5 km h⁻¹ was 3.00, 4.05, and 5.34 L h⁻¹, respectively. Statistical analysis indicated that forward speed had a highly significant ($p < 0.01$) effect on fuel consumption, which increased with increasing operating speed and increased engine power requirement. Similar observations were reported by Marihonnappanavara and Veerangouda (2017) [14]. The effect of forward speed on the performance parameters is presented in Table 1, while the numerical optimization results are shown in Fig. 3.

Table 1: Effect of forward speed on different parameters

Parameters	Speed (km/h)			Average	CD	CV (%)
	1.0-1.5	1.5-2.0	2.0-2.5			
EFC (ha/h)	0.108	0.1314	0.1595	0.123	0.012	5.65
FE (%)	83.07	67.5	61.21	70.6	2.98	3.77
FC (l/h)	3	4.05	5.34	4.13	5.834	8.49

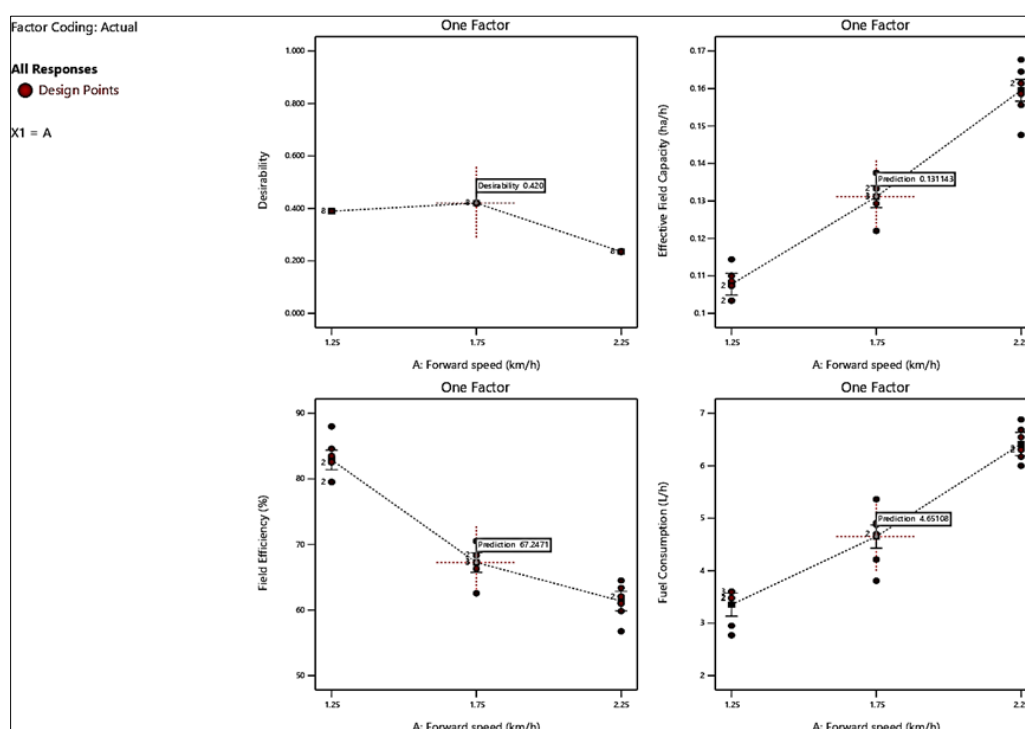


Fig 3: Effect of forward speed on performance parameters of the integrated plastic mulch application system

The numerical optimization indicated that a forward speed of 1.5 – 2.0 km/h provided the most desirable operating condition, with a desirability value of 0.420. At this speed, the predicted effective field capacity, field efficiency, and fuel consumption were approximately 0.131 ha/h, 67.35%, and 4.65 l/h, respectively. These results suggest that the intermediate operating speed offers an appropriate balance between field productivity, operational efficiency, and energy consumption, making it the optimum speed for the developed integrated plastic mulch application system.

Cost of Operation

The production cost of the mulching machine developed as an attachment for a tractor-operated rotavator was estimated by considering the cost of materials and fabrication labour. In this study, the production cost was considered equivalent to the initial purchase cost of the machine. The annual utilization of the tractor and the developed implement was assumed to be 1000 and 200 h, respectively. The operating cost of the developed mulching machine was estimated at ₹767.02 per hour, with a payback period of 5.87 years and a benefit–cost ratio of 1.71, indicating its economic feasibility under the considered operating conditions.

Conclusion

The developed rotavator-powered integrated plastic mulch application system performed satisfactorily under field conditions, producing uniform bunds and laying the plastic mulch sheet without tearing or significant displacement. The machine achieved an overall average effective field capacity of 0.1328 ha/h, field efficiency of 70.59%, and fuel consumption of 4.13 l/h, demonstrating its suitability for mechanized plastic mulch application. The cost of operation was estimated at ₹767.02 per hour (₹5771.40 per hectare), with a payback period of 5.87 years, indicating its economic feasibility for commercial use. Numerical optimization using Design-Expert® identified an optimum forward speed of 1.75 km/h, corresponding to a predicted effective field capacity of 0.131 ha/h, field efficiency of 67.35%, and fuel consumption of 4.65 l/h, with an overall desirability value of 0.420. These findings demonstrate that the developed machine can effectively integrate rotary tillage, bund formation, and plastic mulch laying in a single pass, thereby improving operational efficiency, reducing field operations, and lowering labour requirements compared with conventional multi-pass methods.

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Declarations

Ethical Approval and Consent to Participate: Not applicable.

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Competing Interest: The authors declare no competing interest.

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