Spanish Journal of Agricultural Research
19 (4), e02R01, 14 pages (2021)
eISSN: 2171-9292
https://doi.org/10.5424/sjar/2021194-18387
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)

REVIEW ARTICLE

OPEN ACCESS

Active-passive and passive-passive configurations of combined tillage implements for improved tillage and tractive performance: A review

Pranay Sarkar[1], Ganesh Upadhyay[2] and Hifjur Raheman[1]

[1] Indian Institute of Technology Kharagpur, Dept. Agricultural & Food Engineering, West Bengal 721302, India [2] CCS Haryana Agricultural University, College of Agricultural Engineering and Technology, Dept. Farm Machinery and Power Engineering, Hisar, Haryana 125004, India

Abstract

Proper selection of energy-efficient agricultural machinery helps to reduce drudgery, increase cropping intensity and reduce time required for field preparation. With conventional tillage implements, multiple passes are required to obtain desired seedbed which increase soil compaction due to repeated movement of tractor in field. With combined tillage implements two or more tillage implements are combined to reduce time and fuel energy required for seedbed preparation. In this paper, various researches on active-passive and passive-passive configurations of combined tillage implements have been discussed along with their working principles. It was found that these were associated with less draft, specific energy, and tire slippage compared to conventional implements which provides a sound basis for using them with suitable engine power to improve the power utilization of tractors. Hence, use of these implements could help to reduce soil compaction, labour, fuel cost as well as save time in preparing seedbed. More analytical studies and classical approaches are needed to predict energy requirements of these implements from the knowledge of individual energy requirements of conventional implements to help in proper matching of tractor-implement and also to develop decision support systems. Considering their promising outcomes, they will emerge as effective tools to improve agricultural mechanization.

Additional key words: tractor-implement matching; draft; torque; soil compaction; agricultural mechanization.

Abbreviations used: C-DH (cultivator + single-acting disc harrow); CI (cone index); DSS (decision support systems); PTO (power take-off)

Authors' contributions: All the authors equally contributed to the writing of the paper and to its content.

Citation: Sarkar, P; Upadhyay, G; Raheman, H (2021). Active-passive and passive-passive configurations of combined tillage implements for improved tillage and tractive performance: A review. Spanish Journal of Agricultural Research, Volume 19, Issue 4, e02R01. https://doi.org/10.5424/sjar/2021194-18387

Received: 18 May 2021. **Accepted:** 18 Nov 2021.

Funding: The authors received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Correspondence should be addressed to Ganesh Upadhyay: ganesh.upadhyay0@hau.ac.in

Introduction

Mechanization in agriculture requires appropriate machinery for increasing cropping intensity, reducing time for fieldwork, reduction in drudgery, and effective use of different crop production inputs and power sources (Mrema *et al.*, 2014; Emami *et al.*, 2018). This helps in increasing the productivity of soil to meet the growing demand for food for the increasing population of the world. Topsoil and subsoil (below 25 cm depth) of agricultural land get compacted with the use of heavy agricultural machinery (Oni & Adeoti, 1986; Alakukku, 1997; Tullberg, 2000). Soil compaction has a significant long-term effect on crop yield and nitrogen uptake (Alakukku & Elonen, 1995). Subsoil compaction is persistent and cannot be removed using conventional tillage (Mehuys, 1984; Ungureanu *et al.*, 2017). Changes in pore size distribution and reduction in microporosity are the major consequences of soil compaction (Alakukku, 1996). Size of implement, contact area and inflation pressure of the tyre, soil type, and water content are major factors affecting the compaction of soil (Gue'rif, 1984; Horn *et al.*, 1995; Smith *et al.*, 1997; Hamza & Anderson, 2005). Due to repeated passes of primary and secondary tillage required for preparing the seedbed, sub-soil layers are getting compacted, resulting in a reduction of yield (Mehuys, 1984; Bottam *et al.*, 2004; Shah *et al.*, 2017; Upadhyay & Raheman, 2019). The soil compaction is often neglected in conventional tillage practices and results in degradation of soil structure and compaction (Rátonyi *et al.*, 2015). Botta *et al.* (2009) reported that until the fifth pass of a two-wheel drive tractor, topsoil is compacted mainly due to ground pressure. Multiple passes of a light vehicle having less than 30 kN axle load through the same track are responsible for subsoil compaction.

The more time required by the conventional tillage practices has either reduced field capacity or resulted in high labour costs for short-working periods, which is uneconomical (Jaleta *et al.*, 2019). The field capacity or area covered per unit time can be improved by increasing the speed of operation or increasing the width of the implement. The cost of operation can be reduced by reducing the number of passes with suitable machinery without compromising the tillage quality. Hence, combining two or more tillage operations at the same time using combined tillage implement, can reduce the cost of operation and produce desired seedbed structures (Manian & Kathirvel, 2001; Upadhyay & Raheman, 2018, 2020a). According to Downs (2003), combined tillage implements also help in reducing time, labour, and fuel costs for seedbed preparation. The combined tillage implements can be a combination of purely active and purely passive implements (active-passive configuration) or a combination of purely passive implements (passive-passive configuration). In purely active tillage implements, the rotating part gets powered by the tractor power take-off (PTO) shaft. But, purely passive tillage implements (trailed implements) do not have any active rotating part and require only the drawbar power of the tractor to operate it (Srivastava *et al.*, 1993). With the passive-passive type of combined tillage implements, tractor power utilization can be improved by proper matching between power available from the tractor and power required to pull the implement (Sahu, 2005; Raheman & Roul, 2013). In conventional tillage practices, the majority of farmers utilize the available tillage implements with any range of tractor power. Any improper matching of implements with tractor results in under-loading of tractor engine further reducing overall power utilization efficiency (Alam, 2000; Mehta *et al.*, 2011; Upadhyay & Raheman, 2018). On the other hand, purely active tillage implements generate forward thrust which pushes the tractor in the direction of travel. This may result in an overload of the PTO driveline and reverse torque on the drive axle transmission (Wismer *et al.*, 1968; Hensh *et al.*, 2021a). This detrimental forward thrust can be subdued by combining active and passive tillage tools in such a manner that the forward thrust developed by the active tool contributes towards lowering the draft force requirements of the passive tool. The drawbacks of purely active and purely passive implements are summarized in Fig. 1.

To overcome the above-mentioned drawbacks of purely active and passive tillage implements, Chamen *et al.* (1979) first implemented the concept of combined tillage practice. They added tines behind the rotor to provide a balance to the forward thrust from the rotor and to break up any smear produced by the blades. Further, Watts & Patterson (1984) developed an active-passive and a passive-passive type of implement, namely 'Dyna drive' and 'Tillage train', respectively. Wilkes & Addai (1988), Shinners *et al.* (1990), Shinners *et al.* (1993), and Weise (1993) worked with the active-passive configurations of combined tillage implements. In the last two decades, several kinds of research on the passive-passive configurations of combined tillage implements have been done by researchers such as Javadi & Hajiahmad (2006), Raheman & Roul (2013), Alkhafaji *et al.* (2018), Ginoya *et al.* (2019), and Alkhafaji (2020). At the same time, Anpat & Raheman (2017), Raheman & Behera (2018), Upadhyay & Raheman (2018, 2020b), and Usaborisut & Prasertkan (2018, 2019) have done valuable research on active-passive configurations of combined tillage implements. Choudhary *et al.* (2021) reported front active and rear passive set of combined offset disc harrow to be the most effective among various tested active tillage treatments in terms of both operational energy and tillage performance criteria.

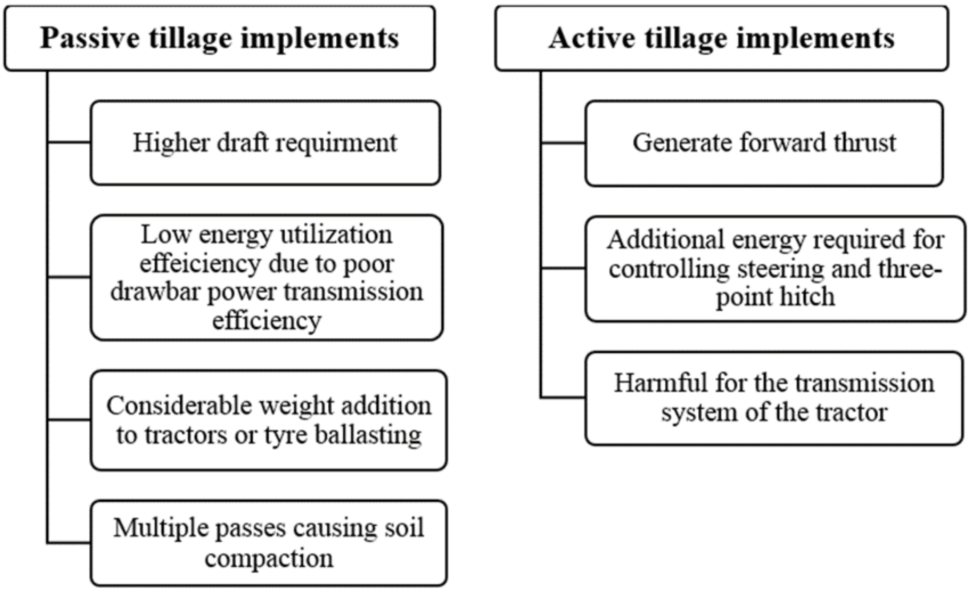

Figure 1. Summarized drawbacks of purely active and purely passive tillage implements.

Furthermore, it may be concluded that active tillage implements help in saving the time and fuel costs during seedbed preparation with improved tillage quality. All the researchers have come to a common conclusion that combined tillage implements require less draft and specific energy requirements for tillage operations. Further, field capacity is increased due to reduced wheel slip and less number of passes required. The performance of an active-passive combination tillage implement depends largely on the working width of the active element in the configuration and the position of mounting the passive element (Chamen *et al.*, 1979; Wilkes & Addai, 1988).

This review paper examines the basic principle, recent developments and performance characteristics of various combined tillage implements, and the ongoing researches on these implements. Research gaps related to combination tillage implements are also discussed. Most of the data regarding this have been taken from various scientific and technical journals to bring all the latest information on the combination tillage together.

Theoretical consideration for combined tillage implements

Based on the theoretical approach on active-passive combined tillage implement proposed by Bernacki *et al.* (1972), a study on the modelling of the power requirement of an active-passive combination tillage implement was carried out by Anpat & Raheman (2017). The specific work of a combined tillage implement consisting of a passive unit and an active unit can be expressed as (Eq. (1)):

$$A_C = \lambda_P A_P + \lambda_A A_A \qquad (1)$$

where, A_C is the specific work of combined tillage implement, N m^{-2}; A_P is the specific work of passive set operating as an individual implement, N m^{-2}; A_A is the specific work of active set operating as an individual implement, N m^{-2}; λ_P and λ_A are the fractions of a specific draft of passive and active implement when working as an individual implement and have values less than unity.

A_C can also be expressed as (Eq. (2)):

$$A_C = A_R + A_T \qquad (2)$$

where A_R is the specific work of combined tillage implement resulting from pulling resistance; A_T is the specific work of combined tillage implement resulting from torque.

Comparing Eqs. (1) and (2), the following equations can be obtained

$$\lambda_P A_P = A_R \qquad (3)$$

$$\lambda_A A_A = A_T \qquad (4)$$

Draft of the combined active-passive configuration, D_C amounts to

$$D_C = D_P + D_X \qquad (5)$$

where, D_P is the draft of passive set in combined tillage implement, N; D_X is the horizontal component of the peripheral force acting on the shaft of active tillage tool, N.

A combined tillage implement, for which D_C is higher than the D_P would be of no practical use. Best combined implement configuration is such that the total power required to pull the implement is less than the drawbar power available from the tractor. An active tillage implement is to be used in concurrent mode in combination tillage implement to reduce the draft of passive tillage implements because of forward thrust generation.

The specific work of individual implements when used in combined configuration can be estimated as:

$$A_P = \frac{D_P}{d_P w_P} \qquad (6)$$

$$A_R = \frac{D_C}{d_C w_C} \qquad (7)$$

$$A_A = \frac{2\pi T_A}{d_A w_A I_g} \qquad (8)$$

$$A_T = \frac{2\pi T_C}{d_C w_C I_g} \qquad (9)$$

where, P, A, and C indicate purely passive, purely active, and combined implement respectively, and the suffice d, w, D, and T stands for depth, width, draft (N), and torque requirement (N-m) of implement, respectively; I_g is the travel length (m) covered by the implement in one full revolution of the shaft of the active set (= 2 π v / ω).

Following relationships can be obtained from Eqs. (4) and (9),

$$\lambda_P = \frac{A_R}{A_P} = \left(\frac{D_C}{d_C w_c}\right)\left(\frac{d_P w_P}{D_P}\right) \qquad (10)$$

$$\lambda_A = \frac{A_T}{A_A} = \left(\frac{T_C}{d_C w_c}\right)\left(\frac{d_A w_A}{T_A}\right) \qquad (11)$$

Considering the depth and width of operation of individual implement to be same as the combined tillage implement *i.e.*, $d_C = d_P$ and $w_C = w_P = w_A$, Eq (11) can be rewritten as,

$$\lambda_P = \left(\frac{D_C}{D_P}\right) \qquad (12)$$

$$\lambda_A = \left(\frac{T_C}{T_A}\right)\left(\frac{d_A}{d_C}\right) \qquad (13)$$

Power requirement of combined tillage implement (P_C) will be

$$P_C = A_C(d_C w_C v) = (\lambda_P A_P d_C w_C v) + (\lambda_A A_A d_C w_C v) \tag{14}$$

$$P_C = (\lambda_P P_P) + (\lambda_A P_A)\left(\frac{d_C}{d_A}\right) \tag{15}$$

P_C can also be expressed as,

$$P_C = (D_C v) + (T_C \omega) \tag{16}$$

where, v is the forward velocity of the combined implement; P_P and P_A are the power requirement of the passive and active sets operating as individual implement; ω = angular speed of the rotating unit.

However, P_C is not the true indicator of the total power requirement of combined tillage implement due to the different transmission efficiencies between the tractor PTO and drawbar. Shinners *et al.* (1993) and Upadhyay & Raheman (2018, 2020a) expressed this total power in terms of the required equivalent PTO power (P_e) of the tractor considering the suitable transmission efficiencies between the tractor PTO and drawbar as follows:

$$P_e = \frac{D \times v}{\eta_{\text{PTO to db}}} + \frac{2 \times \pi \times N \times T}{60 \times \eta_{\text{trans}}} \tag{17}$$

where D is the total draft of the combined implement; v is the forward velocity; N is the rpm of the PTO shaft; η_{PTO} to db is the conversion efficiency from PTO to the drawbar; η_{trans} is the transmission efficiency from PTO to the active set.

Performance characteristics of different configurations of combined tillage implements

One scheme illustrating the concept of passive-passive and active-passive configuration of combination tillage implements is shown in Figs. 2a and 2b, respectively.

Passive-passive configurations

Watts & Patterson (1984) developed a passive-passive type combined tillage implement 'Tillage Train' consisted of two sets of disc harrows. A set of tines with a heart-shaped share were attached in front of the disc harrow gang. The overall work rate and drawbar power requirement were found to be 2.3 ha h^{-1} and 50 kW, respectively while working at depths of 38 to 75 mm. When compared with conventional ploughing, this implement was able to cover three times the area in the same time with nearly one-third of the energy requirement.

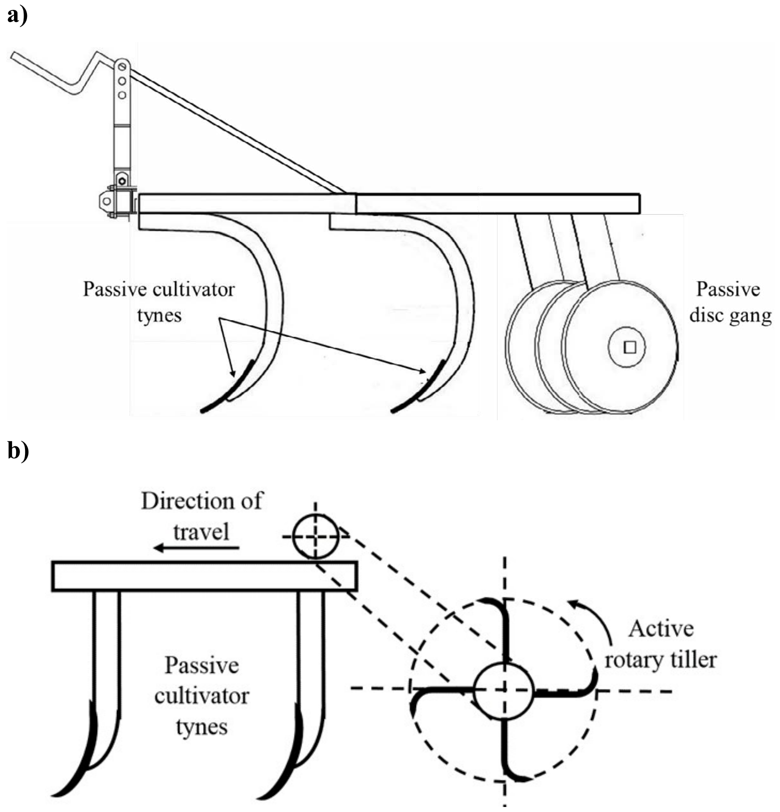

Figure 2. Illustrations of the (a) passive-passive and (b) active-passive configurations of combination tillage implements

Sahu (2005) developed and verified a methodology to predict the draft requirements of passive-passive combination tillage implements from the knowledge of draft requirements of individual tillage implements in undisturbed soil condition and draft utilization ratio of the rear passive set. This model (Eq. (18)) predicted the draft of a cultivator with a disc harrow and mouldboard plough with a disc gang within an average absolute variation of 18.0% and 13.5%, respectively. It was also reported that the draft of tillage implements increased with an increase in soil cone index (CI), working depth, and speed of operation. However, the reverse trend was obtained for the draft utilization ratio (Eq. (19)) with the same parameters. The proposed model is as follows:

$$\begin{aligned} D_c = & \left[\left(\frac{w_{pf}}{w_{rf}}\right)^{m_f}\left(\frac{CI}{CI_s}\right)^{n_f}(C_{1f}+C_{2f}\,v)\,d\right] \\ & + \lambda p\left[\left(\frac{w_{pr}}{w_{rr}}\right)^{m_r}\left(\frac{CI}{CI_s}\right)^{n_r}(C_{1r}+C_{2r}\,v)\,d\right] \end{aligned} \qquad (18)$$

$$\lambda_p = \left(\frac{CI}{CI_s}\right)^{k_2}(a_1 + a_3\,d + a_5\,v) \qquad (19)$$

where, subscripts f and r refer to front and rear passive sets respectively; λ_p is the draft utilization ratio of the rear passive set; D_p is the draft of passive-passive combination tillage implement; w_p is the width of prototype tillage implement; w_r is the width of a reference tillage tool; CI is the soil cone index; CI_s is the cone index of reference soil condition; v is the travel speed; d is the tillage depth; a_i and C_i are the regression coefficients; m is the coefficient of scale factor for implement geometry; n is the coefficient of scale factor for soil parameters; k_2 is the coefficient of scale factor for soil parameters in draft utilization ratio model.

Javadi & Hajiahmad (2006) developed a combined tillage implement comprising a disc harrow and a Cambridge roller. Field testing was carried out with three treatments: ploughing with disc harrow once, disc harrow twice, and combined machine. Lowest bulk density and maximum clod breaking were obtained with combined configuration followed by double discing. Surface uniformity obtained was also highest for the combined configuration. Similar findings were also reported by Loghavi & Hosseinpoor (2002) for mouldboard plough and roller combination. Raheman & Roul (2013) developed a passive-passive combined implement which consisted of a cultivator and a single-acting disc harrow in sequence (C-DH). The combined implement was tested and compared with individual operations of the cultivator and disc harrow. The overall performance of C-DH was expressed in terms of tillage performance index, which is directly proportional to the volume of soil handled and wheel slip; and inversely proportional to mean weight diameter and fuel energy. The draft of C-DH was found to be the highest among the tillage implements tested and showed a polynomial increase with an increase in speed and depth. Slip of driving wheels of the tractor with cultivator, offset disc harrow, and combined implement (C-DH) were found to be within 8.6 to 16.9%, 7.5 to 13.9%, and 10.5 to 22.4%, respectively. The mean weight diameter of soil fragments after C-DH operation was greater than disc harrow operation, because of less pulverization. However, due to the more volume of soil handled, the overall tillage performance index was found to be highest for C-DH. Alkhafaji *et al.* (2018) developed combined tillage implement (mouldboards plough + ripper). This ripper having six shanks was attached to the end of the mouldboards plough chassis. The line of pull of the mouldboard plough passed through the middle of the ripper. The implement was tested with its four configurations by changing the orientation (towards the direction of travel and opposite to the direction of travel) and depth (same depth as plough depth and 0.05 m above plough depth) of ripper shank and mouldboard plough alone. Soil clod size, roughness index, and actual field capacity were measured. The use of combined tillage implement resulted in lesser diameter soil clods than mouldboard plough operation indicating superior tillage quality. Soil clod size increased significantly with an increase in the speed of operation. Less soil surface roughness was achieved in the case of combined tillage implements as compared to mouldboard plough. The configuration with ripper shanks opposite to the direction of travel gave the best performance.

Ginoya *et al.* (2019) developed and optimized a mini tractor-mounted clod crusher cum planker. Cultivator tines and spike tooth roller were provided to open furrow and pulverize the soil, respectively. Clod crushers with square spike, round spike, and square spike arranged spirally were tested. Individual and combined effects of the type and weight of the clod crusher were statistically analyzed. It was suggested to use the clod crusher (with square spike) cum planker due to minimum mean weight diameter of soil particles obtained, slip, fuel consumption, and higher field capacity. Alkhafaji (2020) developed a triple combined tillage implement consisting of three equipment: a mouldboard plough with four shares, rigid tines, and levelling board. Rigid tine for harrowing and levelling board for levelling as additional parts were attached to the mainframe of the mouldboard plough. Its performance was compared with single tillage (four-bottom mouldboard plough) and dual combination tillage (ploughing + harrowing with rigid tines tool). Triple combination tillage achieved the lowest value of bulk density because harrowing after mouldboard plough helped to easily break the ploughed soil and increase the number of air pores in the soil. Levelling operation carried out directly after ploughing assisted in shattering clod to a smaller size and decreased bulk density, especially when ploughing operations were done at the appropriate conditions of soil moisture. The roughness index was significantly lower in the case of triple combined tillage operation. Adding harrow to mouldboard plough resulted in an 8-12%

increase in the slip, and this increment was 17% in the case of triple combined tillage implement. Performance of different passive-passive combined tillage implements discussed above is summarized in Table 1.

Table 1. Summary of performance of different passive-passive configurations of combined tillage implements.

	Reference	Combined implement	Investigation	Soil type (Water content,% dry basis)	Major findings
1	Watts & Patterson (1984)	Tillage train (set of tynes + two sets of disc harrow)	Evaluated the performance of tillage train in the field.	Clay loam, sandy clay loam	Tillage train was capable of high work output with a relatively low energy requirement. The field capacity was three times with nearly one-third of the energy requirement.
2	Sahu (2005)	Mouldboard plough + Disc harrow, Cultivator + Disc harrow	Developed a methodology to predict the draft of passive-passive combined tillage implements from the knowledge of draft of individual tillage implements.	Sandy clay loam (11.6-12.5%)	The developed model estimated the draft of a cultivator with disc harrow and mouldboard plough with a disc gang within an average absolute variation of 18.0% and 13.5%, respectively.
3	Javadi & Hajiahmad (2006)	Disc harrow + Cambridge roller	Compared the performance of developed combined tillage implement with conventional disc harrow operation.	Loamy (39%)	Combined tillage operation resulted in the lowest bulk density, penetration resistance, and maximum uniformity of soil.
4	Raheman & Roul (2013)	Cultivator + Disc harrow (C-DH)	Field tested the developed combined implement (C-DH) and compared its performance with cultivator and disc harrow working separately.	Sandy loam (10.8-12.5%)	Combined implement gave the highest tillage performance index due to the more volume of soil handled and better pulverization than its components working separately.
5	Alkhafaji *et al.* (2018)	Mould board plough + Ripper	Tested the combined implement at different configurations of ripper shank and different speeds of operation.	Clay	Recommended the orientation of ripper shank opposite to the direction of ploughing for better results. Combine tillage implement produced more uniform soil than mouldboard plough when operated alone.
6	Ginoya *et al.* (2019)	Clod crusher + Planker	Tested a developed clod crusher roller cum planker and studied the effect of different types of spikes on soil properties.	Sandy loam (14.18%)	The combined arrangement broke the soil clods properly and resulted in optimum bulk density and mean weight diameter. It was suggested to use a square spike in the clod crusher.
7	Alkhafaji (2020)	Mould board plough + Harrow + Levelling board	Developed triple combined tillage implement and compared the performance with dual and single tillage implements.	Clay	The lowest bulk density and roughness index were achieved by triple combined tillage implement. Wheel slippage increased from 8% to 17% when harrow and leveler were added to the mouldboard plough.

Active-passive configurations

Chamen *et al.* (1979) identified soil blockage and poor soil penetration as two major problems during the operation of a rotary digger. Rigid scrapers were used to prevent soil blockage and were fixed behind the machine projecting into the gap between the sets of blades. The second problem was overcome by setting the rotor blades with equal angular distance. Forward thrust from the rotor was balanced by adding tines. These tines loosened the soil at greater depth and kept implement working with a vertical downward force at higher working speeds. The performance of this rotary digger was also compared with conventional plough and shallow depth plough. Soil strength was measured for consecutive two years after rotary digger and conventional plough operation and little evidence of soil pan was found at rotor depth. The visual estimation of soil structure after the operation of rotary digger and the conventional plough was carried out by Peerlkamp *et al.* (1967) and Batey (1975) over three years and better soil structure was found in the case of rotary digger operation. Crop yields were studied after combined rotary digger operation along with the other three treatments over four years. During the first two years, less crop yield was found for combined rotary digger, but in the third year, a significantly greater yield was reported. Watts & Patterson (1984) developed an active-passive type combined tillage implement comprised of two rotors, called ‘Dyna Drive’. The front one was soil-driven and the second one was driven with a chain drive by the front one with three times faster speed. In light soil, it could prepare the seedbed in single pass, but under hard soil conditions, two passes were recommended. Wilkes & Addai (1988) developed a combined tillage tool known as the ‘Wye Double Digger’ consisting of a rotary subsoiler and a mouldboard plough bottom. The rotary subsoiler loosened the opened furrow and the mouldboard bottom turned the next soil slice onto the loosened subsoil. The ‘Wye Double Digger’ performed better with less draft, specific energy requirement, and wheel slip compared to the mouldboard plough operating alone at the same depth.

Shinners *et al.* (1990) measured draft and specific energy of a combination tillage implement comprising two rotors and four passive chisels along with four other machine configurations (2 Passive + 2 Active, 2 Active, 2 Passive, and 4 Passive). The effect of depth ratio and bite length on draft requirement was studied. No significant variation in total power requirement was observed in implements configured with the same number of active elements. Combined implement configured with two passive and two active elements required 0.6 kW less power than implement with four passive elements due to the negative draft produced by the active elements. Increasing bite length reflected a significant increase in PTO power requirement. The depth of operation played a significant role in the draft requirement when only the passive configuration was concerned. But when active elements were present, the increased draft due to greater depth was compensated by a greater negative draft generated by active elements. With an assumption of power transmission efficiencies, it was predicted that the developed combined implement would be 34% energy-efficient than a similar passive tillage implement. Weise (1993) investigated the dependency of drawbar power and PTO power on forward speed of a combined tillage implement consisting of wing share and tine rotor cultivator. He reported that with an increase in forward speed, the total power requirement of the combined implement went up very high compared to the tine rotor when operated alone. He suggested not to operate this type of implement at very high speed. It was also observed that when the necessary tine speed for crumbling the clods reached, a further increase in rotor speed caused no further reduction in clod size. This was because, at unnecessarily high rotor speed, the energy was not being used for further disintegration of clods, but wasted in the thrust generation and mechanical losses.

In another experiment, Shinners *et al.* (1993) studied the effect of velocity ratio (ratio of rotor tip velocity to forward velocity), depth ratio, and forward speed on the performance of an active-passive tillage implement. They observed a higher negative draft at lower forward speed, greater rotor tip velocity, and active/passive depth ratio. A lower slip occurred under the same conditions. Based on their findings, they suggested that the lighter tractors could be used to operate the active-passive tillage machine. This could lead to increase field productivity and reduce soil compaction. Manian *et al.* (1999) used a combination tillage bed furrow former in red loam and black clay loam soil to utilize the negative draft produced by rotary tools and to conserve moisture by forming furrows. Significant changes in soil physical properties were observed using the combination tillage bed furrow former with bulk density reduced from 1.54 g cm^{-3} to 1.23 g cm^{-3} in red loam soil, and from 1.49 g cm^{-3} to 1.26 g cm^{-3} in black clay loam soil. Manian & Kathirvel (2001) developed a combined tillage implement with a rotary cultivator (16 rotating blades) as an active unit and four chisel type shares as a passive unit. Draft of the combined tillage implement increased with an increase in forward speed. For the passive tool, the slip increased steadily as the forward speed increased. But for the active tool and its combination with the passive tool, the rate of increase in slip was less which indicated the role of negative draft produced by the active tool. Adding four passive elements to active tools resulted in a 20% reduction in fuel consumption as compared to when the active tools were operated alone. It showed that a negative draft was better utilized by adding four passive elements.

Kailappan *et al.* (2001) stated that moisture status in subsoil can be improved by tilling with combined implements after disc plough or mouldboard plough operation. Because this helps to form smaller size clods and their arrangement in the soil layer. They reported that 44–55% of the cost and 50–55% of the time could be saved in seedbed preparation by using a combination tillage tool. Hegazy & Motalleb (2008) developed a combined implement consisting of a chisel unit and rotary plough. The tillage systems compared in this study were combined tillage unit (single pass), rotary tiller after chiseling once, and chisel plough three passes. Soil bulk density and draft requirement increased with increase in forward speed for all the treatments. Combined tillage resulted in a minimum bulk density of soil and the least fuel consumption. The yield of sugar beet increased with an increase in tilling depth. A comboplough consisting of a disc plough and rotary blades was developed and tested by Hashemi *et al.* (2014). Experiments were carried out with three types of blades (straight type or S blade, L-shaped, and C-shaped) and three rotary speeds (165, 147, and 130 rpm). Types of blades did not affect the soil properties significantly. But significant changes in soil properties were observed at different speeds. The mean weight diameter (dry basis) decreased with increase in the rotational speed of the blade. This indicated that slow hitting of the soil by the rotary blade produced larger diameter clods. Parmar & Gupta (2016) added a PTO-operated pulverizing attachment to the cultivator. The pulverizing roller had helical blades to pulverize soil to a greater degree. The pulverizing blades ran in helix pattern from one disc to another in such a manner that at a time only one portion of a particular blade would remain in contact with the ground. A lesser wheel slip of 4.01% was recorded for this combined implement due to the simultaneous operation of active and passive units. Less draft requirement of the total assembly was also reported due to the pushing effect of the roller.

Anpat & Raheman (2017) investigated draft and torque requirement of active-passive tillage implement (cultivator in the front and rotavator in the rear) in a laboratory soil bin with sandy clay loam soil and developed prediction equations for draft and torque. Cone index, velocity ratio (peripheral speed of the active element to the forward speed of machine), and depth ratio of active and passive tools were selected as variable parameters. The width of the implement, velocity ratio, and cone index had a linear relationship with the draft and torque of the implement. But, the depth ratio showed a logarithmic relationship with the draft of the implement. The developed equation for estimating power requirement was validated with another set of data and the maximum absolute difference between the estimated and observed values of power was found to be 12.43%. A draft-calculating model and a torque calculator were developed for a subsoiler and rotary tiller, respectively (Ahmadi, 2016, 2017a). Ahmadi (2017b) developed an estimator for prediction of performance parameters of combined tillage implements by modifying and combining these calculators. Values of soil strength and pore characteristics were considered from the research of Schjønning & Rasmussen (2000) in this estimator. This estimator was verified by comparing its outputs with the results from Chamen *et al.* (1979), Shinners *et al.* (1993), Weise (1993), Manian & Kathirvel (2001), and Anpat & Raheman (2017). The outputs of this estimator were reported to be aligned with the results from those researches. Raheman & Behera (2018) developed a rota-cultivator for better pulverization of soil. It comprised of a gang of five reversible-shovel type cultivator tines attached at the front of a rotary cultivator comprising 36 numbers of L- type rotary blades with a total working width of 1.6 m. The cutting width of a single row of cultivator and rotavator was kept the same. The performance of the tillage implement was expressed in terms of tillage performance index considering the volume of soil handled per unit time, the percentage reduction in cone index, and fuel energy required to carry out tillage. The torque, PTO power, and draft requirement of the rota-cultivator decreased when the velocity ratio (ratio of peripheral speed of the blade to forward speed) was increased at a constant operating depth. Increasing depth of operation resulted in higher torque requirement of rota-cultivator. Similar findings were also reported by Ghosh (1967), Shibusawa (1993), Anpat & Raheman (2017), and Hensh *et al.* (2021b). The clod size decreased with an increase in velocity ratio *i.e.* with a decrease in forward velocity of the tractor. The tillage performance index of the rota-cultivator was found to be maximum at a velocity ratio between 5 and 6.

Upadhyay & Raheman (2018) investigated the effect of front gang angle, velocity ratio, operating depth, and cone index on draft, torque, and power requirement of a combined offset disc harrow having a front active and rear passive set configuration, under controlled conditions in a soil bin. The performance was also compared with its traditional passively driven mode. It was reported that the draft requirement of this implement decreased significantly with an increase in velocity ratio similar to the findings of Hoki *et al.* (1988), Hann & Giessibl (1998), Nalavade *et al.* (2010), and Upadhyay *et al.* (2017). The higher velocity ratio resulted in a decrease of the specific torque requirement at all tested conditions. Draft of this active-passive configuration was always found to be less with better pulverization and loosening of soil as compared to conventional passively driven offset disc harrow. The best system settings for this type of implement were found at a front gang angle of 35° and velocity ratio of 3.6 in terms of lowest power expenditure and better work quality.

A combined tillage implement consisting of a subsoiler, a vertical axis rotary harrow, and a bar case roller was tested by Usaborisut & Prasertkan (2018) using four different linkage configurations. The most suitable linkage configuration was that where the force of the rotary harrow was acting on the shank above the pivot point. In this configuration, the required draft was 11.3% lesser than other configurations due to the different geometrical and kinematic relationships of the mechanism. Lesser draft reduction was observed in the case of the vertical axis rotor compared to the horizontal axis rotor by Shinners *et al.* (1993). This might be due to the fact that the vertical axis rotor used soil resistance reaction to push, whereas the horizontal axis rotor generated impact while cutting the soil. A significant increase in the drawbar power and average PTO power was observed with an increase in the forward speed for the active-passive configuration by Usaborisut & Prasertkan (2018), which is in line with previous work conducted by Upadhyaya *et al.* (1984), Weise (1993), Shinners *et al.* (1993), and Ranjbarian *et al.* (2015). It was because of more force required to cut the soil of longer bite-size at higher forward speed of tool (Ahaneku & Ogunjirin, 2005). Increasing rotor speed increased the PTO power requirement similar to the findings of Walton & Warboys (1986) and Kouchakzadeh & Haghighi (2011). The active-passive combined implement by Usaborisut & Prasertkan (2018) reduced the draft and power requirement of subsoiling by 4.4% to 11.3% and 10.5% to 15.3% compared to the subsoiler when operated alone. Previous works conducted by Shinners *et al.* (1990), Weise (1993), and Ahmadi (2017a) showed a similar phenomenon. Upadhyay & Raheman (2020a,b) conducted field tests to evaluate the performance of combined offset disc harrow consisting of six notched type concave discs at the front and six plain type concave discs at the rear. The front gang was actively rotated using tractor PTO shaft. They studied the effect of velocity ratio on performance parameters such as draft, torque, wheel slip, specific energy requirement, and tillage performance index. Increasing velocity ratio produced a decrease in specific energy requirement up to a certain point, after that, it increased rapidly due to throwing of soil (parasitic loss) with higher kinetic energy. They reported crop residue burial efficiency and pulverization of the soil clods to be increased with an increase in velocity ratio. The developed combined active-passive configuration was found to be effective in handling the crop residues left after paddy harvesting and further helped to achieve timeliness in completing seedbed preparation in the rice-wheat cropping system, where narrow time window is available between the harvesting of paddy and sowing of wheat. They suggested to maintain the velocity ratio between 3.0 and 4.0 for this type of combined tillage implement to achieve the maximum tillage performance with minimum energy consumption.

Nataraj *et al.* (2021) developed a microcontroller-based embedded digital display and warning system for measuring tyre slippage, velocity ratio, PTO torque, and draft requirement of any purely active or active-passive tillage machinery. Their developed system helped to guide the operator in controlling the performance of tillage machinery involving active tools for achieving better soil tilth with less energy inputs.

The performance of different active-passive combined tillage implements discussed above is summarized in Table 2.

Table 2. Summary of performance of different active-passive configurations of combined tillage implements.

	Reference	Combined implement	Investigation	Soil type (Water content,% dry basis)	Major findings
1	Chamen *et al.* (1979)	Rotary digger + Chisel tynes	Field-tested a rotary digger consisting of a horizontal rotary cultivator and deep chisel tines mounted behind the rotary cultivator.	Heavy clay (20.8%)	The net energy requirement of the rotary digger was 50% lesser than the conventional plough with higher efficiency.
2	Watts & Patterson (1984)	Dyna drive (Soil driven rotor + Rotor driven by the first rotor)	Evaluated the performance of Dyna Drive.	Clay loam, sandy clay loam	Dyna drive was capable of high work output with a relatively low energy requirement. The field capacity was three times with nearly one-third of the energy requirement.
3	Wilkes & Addai (1988)	(Wye double digger) Rotary subsoiler + mouldboard plough bottom	Evaluated the performance of a combined implement consisting s rotary subsoiler and a mouldboard plough and compared with mouldboard plough when operating alone.	—	The combined one required less draft, specific energy requirement, and resulted in less slip than mouldboard plough.
4	Shinners *et al.* (1990, 1993)	Rotor + Chisel tyne	Compared a combination implement consisting of two active and two passive chisel elements with a tool having four passive elements.	Silty clay loam, and silt loam (17.2-25.7%)	The combination implement was found to be 34% more energy-efficient as compared to a similar passive tillage tool. The speed ratio was the most significant factor affecting the performance of the combination implement.
5	Weise (1993)	Tine rotor cultivator + Wing share + Roller	Investigated draft and power requirement of a combined tillage implement consisting of wing tines at the front followed by a tine rotor.	Silt loam and silty clay loam (26%)	The pre-loosening of the soil by wing tines reduced the energy requirement of the rotor. An increase in the rotor rpm beyond a certain point did not help in further reducing the clod size.
6	Manian & Kathirvel (2001)	Rotary cultivator + Four chisel type share	Tested a combination tillage implement consisting of sixteen tine rotary tiller and four chisel type shares at different speeds and configurations.	Black clay loam soil	Fuel consumption, energy, time, and cost of operation for combination tillage implement were reduced as compared to different implements when operated separately to obtain almost the same quality of tilth.

Table 2 Continued.

	Reference	Combined implement	Investigation	Soil type (Water content,% dry basis)	Major findings
7	Hegazy & Motalleb (2008)	Rotary plough + Chisel unit	Developed a combined implement consisting of a rotary unit and chisel unit and compared this with traditional methods for seedbed preparation.	Clay soil (16.35-22.40%)	Combined tillage produced better results in terms of soil bulk density, infiltration rate, slip percentage, and fuel consumption than traditional methods.
8	Hashemi *et al.* (2014)	Disc plough + Set of rotary blades	Studied the effect of type of blades (straight type or S blade, C-shaped, and L-shaped) and forward speed of soil characteristics.	Clay loam	Types of blade did not affect the soil properties significantly. But significant changes in soil properties were observed at different speeds.
9	Parmar & Gupta (2016)	Cultivator + Pulverizing roller	Developed and evaluated the performance of combined cultivator and PTO operated pulverizing roller for seedbed preparation.	Medium black (12.5%)	The combined implement performed satisfactorily in the field, and fuel consumption and cost of operation were found lesser than other tillage implements.
10	Anpat & Raheman (2017)	Cultivator + Rotavator	Tested a combination tillage implement having cultivator at front and rotavator at the rear in the laboratory soil bin	Sandy clay loam (10.5%)	The power requirement of the combination implement was lesser than the total power requirement of individual implements (*i.e.*, cultivator and rotavator alone). Recommended a velocity ratio of around 7.0 for this type of combination implement for minimizing power requirement.
11	Raheman & Behera (2018)	Rotavator + Cultivator	Developed a rota-cultivator and evaluated its performance at three different gears and two depths of operation.	Sandy clay loam (11%)	The torque, PTO power, and draft requirement decreased with an increase in velocity ratio and increased with an increase in depth of operation. It minimized soil compaction by reducing the number of passes.
12	Upadhyay & Raheman (2018)	Combined offset disc harrow (Front gang active + Rear gang passive)	Soil bin testing of combined offset disc harrow (front gang active and rear gang passive).	Sandy clay loam (9-10%)	The combined offset disc harrow could provide better pulverization and reduction in cone index value of soil with a minimum increase in power requirement than conventional disc harrow. Optimum system settings were found at front gang angle of 35° and velocity ratio of 3.6 in terms of lowest power expenditure and better work quality.
13	Usaborisut & Prasertkan (2018, 2019)	Subsoiler + Vertical axis rotary harrow + Bar case roller	Field tested a combined tillage implement consisting of a subsoiler and a rotary harrow (joined using four different linkage configurations).	Clay and clay loam (16.6%)	Combined tillage implement required 10.5% to 15.3% reduced total power compared to the combined power required by the subsoiler and rotary harrow working separately. One pass of the combined implement produced the same results as the use of subsoiler and rotary harrow separately.
14	Upadhyay & Raheman (2020a)	Combined offset disc harrow (Front gang active + Rear gang passive)	Investigated the effect of velocity ratio on the field performance of combined offset disc harrow.	Lateritic sandy clay loam (11%)	Wheel slippage, draft, and torque requirement decreased with an increase in velocity ratio. The specific energy requirement was minimum at a velocity ratio of 2.91. Recommended a velocity ratio between 3.0 and 4.0 for this type of implement to achieve the maximum tillage performance with minimum energy consumption.
15	Upadhyay & Raheman (2020b)	Combined offset disc harrow (Front gang active + Rear gang passive)	Comparative analysis was carried out between an active-passive combined offset disc harrow and a conventional passively-driven offset disc harrow	Lateritic sandy clay loam (102-117 g kg^{-1})	The soil pulverizing ability, stubble cutting, and crop residue burial efficiency was observed to be better with combined offset disc harrow compared to passively-driven offset disc harrow. Better penetration ability and uniformity in tilling depth was also observed.

Conclusion and perspectives

More than twenty configurations of combined tillage implements along with related research have been discussed here. The number of developments of new combined implements and analytical research on them during different decades as discussed in above section is summarized in graphical form in Fig. 3. Most of the researches (12 out of 20) on combined tillage implements has been conducted from 2011 to 2020. A summary of drawbar power, PTO power, and total power requirement of some of those developed implements are shown in Table 3. So far only nine researchers have described all the operational parameters such as working width, depth, and speed; energy consumption parameters such as drawbar power, PTO power, and fuel consumption; and tillage quality parameters such as soil pulverization, soil inversion, and crop residue burial efficiency. More analytical studies and alternative approaches are needed in this regard to predict the energy requirements of these tillage implements from the knowledge of individual energy requirements of conventional tools, to help in proper matching and to develop decision support systems (DSS) for tractor-combination tillage implement system. Acceptance of combined tillage implements among the farmers is required for improving mechanization. In Asian countries, this innovation is in the research stage and new configurations (combination

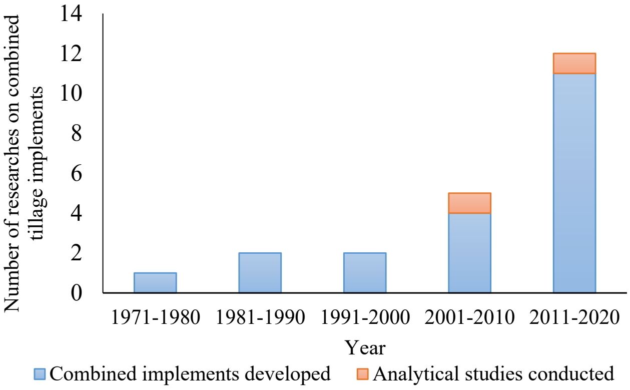

Figure 3. Summarized data on number of decade wise researches published on combined tillage implements.

Table 3. Power requirements of different combined tillage implements.

	Implement configuration	Width (m)	Operating conditions: Forward speed (km h^{-1})	Operating conditions: Depth (mm)	Drawbar power (kW)	PTO power (kW)	Total power (kW)	Reference
1	Tillage train (set of tynes + two sets of disc harrow)	-	8.9-11.1	38-75	37-63	-	-	Watts & Patterson (1984)
2	Rotor + Chisel tyne	2.6	-	15-230	6.16-10.20	12.23-31.32	18.39-41.52	Shinners *et al.* (1990)
3	Rotor + Chisel tyne	6 elements with 380 mm spacing	4.8-8	300 (passive element), 190-300 (active element)	-5.7 to 33.7	16.9-53.4	-	Shinners *et al.* (1993)
4	Rotary cultivator + Four chisel type share	1.24	1.72-3.28	150-250	1.60-5.66	7.35-8.49	8.96-14.16	Manian & Kathirvel (2001)
5	Mouldboard plough with disc gang implement	1.2	1.7-4.5	145-188	1.28-7.62	-	-	Sahu (2005)
6	Cultivator with a single-acting disc harrow	2.1	2.6-4.9	65-100	1.03-7.04	-	-	Sahu (2005)
7	Rotavator + Cultivator	1.55	2.21-4.35	80-120	-	-	7.2-15	Raheman & Behera (2018)
8	Subsoiler + Vertical axis rotary harrow + Bar case roller	1.00	1.79-3.33	200 (rotary harrow), 400 (subsoiler)	17.15-22.77	11.59-15.12	-	Usaborisut & Prasertkan (2019)
9	Combined offset disc harrow (front active and rear passive set)	1.45	3.46-6.82	120	2.68-9.07	7.34-14.24	12.19-27.81	Upadhyay & Raheman (2020a)

of tillage implements), more efficient power transmission for minimizing losses need to be explored. This will help to increase the use of combined tillage implements, which will emerge as powerful machinery for agricultural mechanization.

In this paper, a broad overview of the various developed configurations of combined tillage implement is presented. Previous researches on combined tillage implements showed very promising outcomes. The conclusions drawn from the previous studies provide a sound basis for using combined tillage implements with suitable tractor engine power in the current farming system to improve the power utilization of tractors. The different passive-passive configurations were found to outperform the conventional tillage practices in terms of fuel consumption, time requirement, and cost of operation. On the other hand, with active-passive configurations, the forward thrust developed by the actively rotating tools can be managed efficiently with better utilization of the engine power of tractor. These implements are energy efficient and require less number of passes than conventional tillage practices to achieve the desired seedbed conditions. As the combined implements could prepare seedbed with reduced number of passes, this could further help to reduce the soil compaction problem induced by vehicular traffic. Further research is needed in this regard to study the effect of combined tillage operation on the long-term yield of crops.

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