



Review article

Design optimization of rotary tiller blades: a critical review

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ABSTRACT

Tillage is an operation performed to obtain a desirable soil structure for a seedbed or root bed. A granular structure is desirable to allow rapid infiltration and good retention of rainfall and to minimize resistance to root penetration. Rotavator (also called rotary tiller) is a tractor operated cultivating implement that breaks or works the soil with the help of rotating blades. The use of rotavator is increasing due to its versatility in doing a good quality tillage job with minimum number of passes. The rotavator do simultaneous ploughing and harrowing in dry and optimum soil moisture in single operation. The blades are the main critical parts of a rotary tiller which are engaged with soil. So, wearing takes places at the cutting edges of these blades due to high stresses are coming. In this context a lot of research on rotavator blade has been carried out in different parts of the world. This paper briefly reviews the work done so far on the rotary tillers' blade design optimization and development.

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1. Introduction

A rotary tiller is a specialized mechanical tool used to plough the land by a series of blades which are used to swirl up the earth. Rotary tillers have become world famous for seedbed preparation. These equipments are often used for breaking or working the soil in lawns, gardens, etc (Hendrick & Gill, 1971c). Nowadays, utilization of rotary

tillers has been increased in agricultural applications because of simple structure and high efficiency of this type of tillage implements. By taking advantage of rotary tillers, the primary and secondary tillage applications could be conjugated in one stage (Topakci et al., 2008). Rotary tillers have now become accepted cultivation implements for both farm work and horticulture not only in India but also in several foreign countries. Despite of their high energy consumption, since rotary tillers have the ability of making several types of tillage applications in one stage, the total power needed for these equipments is low (Culpin, 1981). Because rotary tillers power is directly transmitted to the tillage blades, the power transmission efficiency in rotary tillers is high. Power to operate the rotary tiller is restricted by available tractor power (Yatsuk et al., 1981; Srivastava et al., 2006).

Rotavator mostly available with working width of 1.20–1.80 m, which is suitable for tractors having 45 hp and above. Further, rotavator may have 'L' shape, 'C' shape, 'J' shape, hook tines and straight knife blades to suit various operating conditions (Fig.1). L-shaped blades are better than hook-shaped or pick type blades in trashy conditions, they are more effective in killing and they do not pulverize the soil as much (Adams, 1959). The detail of an L-shaped blade is shown in Fig.2. L-shaped blades are used mostly in Indian rotavator which are normally mounted with three right handed and three left handed blades per flange as shown in Fig.3.

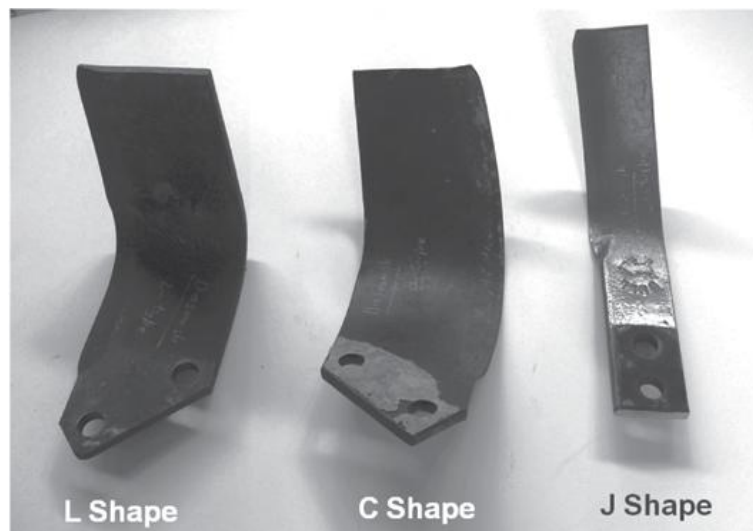


Fig. 1. Different types of rotavator blade (Mahal et al., 2012).

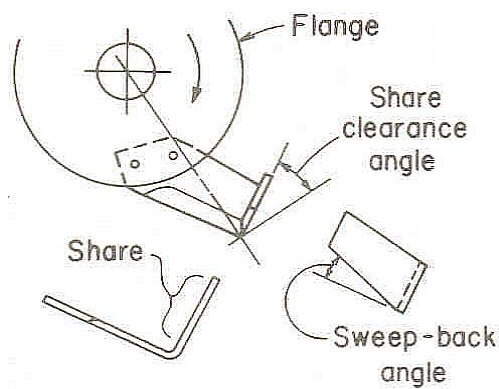


Fig. 2. Three views of an L-shaped blade for rotary tiller (Kepner et al., 1977).

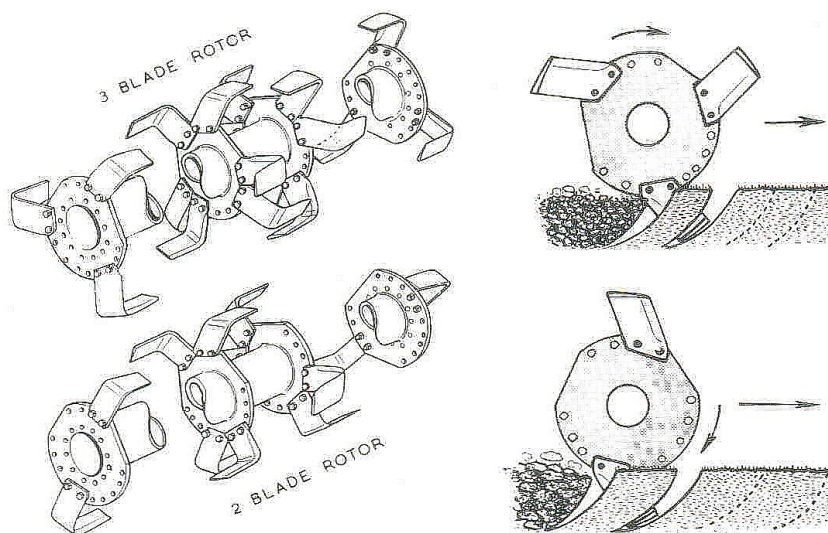


Fig. 3. Rotary tiller rotors with L-type blades showing methods of mounting and cutting action (Culpin, 1981).

Rotary tillers prepare the seed bed fundamentally different than the conventional method of plowing. The soil is pulverized by the cutting and chopping action of a number of blades that receives energy from the engine of the prime mover (Salokhe and Ramalingam, 2001). As per as the quality of the seedbed is concern, one pass of the rotary tiller is equivalent to several conventional tillage operations (Mandang et al., 1993).

The work quality by using a rotavator not only depends on design parameters but rotor blade layout, speed of rotors, forward speed significantly affects the machine performance. When a tillage operation is performed in the field, the soil texture will be a function of soil conditions, blade geometry and soil flow dynamics. Depending on the soil conditions, blade geometry and velocity ratio, the interference of the backside of the blade and the uncut soil may result in severe soil compaction and high power consumption. This is the main reason to cause vibrations, which are a result of the reaction of soil upon the tiller blades. The proper design of the rotary tiller blades is essential to efficient operation (Mahal et al., 2012).

However in a rotary tiller, blades are the main critical parts which engaged with soil to prepare the land. These blades interact with soil in a different way than normal plows which are subjected to impact and high friction which ultimately creates unbalancing and non uniform forces on the rotary tiller which results wearing of the blades as a whole. Therefore, it is necessary to optimize the design of blade so that these blades experience less stress thereby reduces the wear.

The continuous fluctuating impact of soil crust / clods / stone develops high stress areas on blade tip or blade critical edges. A rotavator has a useful life of 2400 h (8 year) with annual use hour as 300. The local blades need replacement after 80-200 h of their use; however, imported blades need replacement after 300-350 h in normal soil. The local and imported blade sets are changed 23 times and 7 time respectively during their entire service life. It is estimated that around 5 lakhs blades are required annually towards replacement and for new machines. (Saxena and Singh, 2010). Therefore, proper design of these blades is necessary in order to increase their working life time and reduce the farming costs (Mollazade et al., 2010).

Wear is the major reason, which limits the durability of many agricultural tools. Agricultural soil-cutting tools have their own characteristics of wear, which are different from other types, since they interact with soils of various textures, moistures and other unpredictable conditions in the field. Among the soil cutting agricultural tools currently used, the rotary tiller is one of the most promising pieces equipment, saving operating time and labour. One rotary tillage may be equivalent to several conventional tillage operations. Although the rotary tiller is an energy and time efficient pieces of equipment, rapid wear of the tiller blades, typically made from medium carbon steels, in certain conditions may restrict its use. Heat treatments are often carried out to provide protection to the blades in order to lengthen the service life of the carbon steel blade and, hence, reduce the total cost of agricultural production. In practice, though, it is found that the heat treated blade may not provide satisfactory protection in harsh field conditions. High wear rate is still observed, resulting in routine blade

replacement during tillage (Karoonyboonyanan et al., 2007). Hence there is a need to design suitable blade so that these problems will be overcome.

Again in India, because of variety of soil conditions in different regions, different blades are used, but most of the blades faces similar problem like high rate of wear which ultimately reducing the service life/working life. Working life time of the blades can be increased by a suitable design according to the soil type and soil condition. Thus it is necessary to design suitable rotary tiller blade through design optimization and finite element analysis interrogation so as to increase the useful life of the tiller blade in order to reduce the idle time required to replace the blade periodically during soil preparation.

2. Tillage

Tillage may be defined as the mathematical manipulation of soil to develop a desirable soil structure for seedbed or root-bed, to control weeds, to manage plant residues, to minimize soil erosion and to establish specific surface configurations for planting, irrigation etc. Tillage operations for seedbed preparations are often classified as primary or secondary. A primary tillage operation constitutes the initial, major soil-working operations; it is normally designed to reduce the soil strength. Secondary tillage operations are intended to create refined soil conditions. The moldboard plow is most commonly used for primary tillage. Rotary tiller's or rotavator are being used now days as a secondary tillage implements as these tool obtain their energy in more than one manner, energy from a rotary source usually the tractor PTO. Reduced draft requirements and greater versatility in manipulating the soil to obtain a desired result are the two reasons for considering these more complex types of equipments. If draft requirements can be reduced by utilizing at least part of tractor's output through PTO, the tractor can be made lighter which will reduce its cost and reduce soil compaction. Therefore it becomes necessary to use minimum tillage systems for the purpose of to reduce the mechanical energy and labor requirements, to conserve moisture and to minimize the number of trips over the field. Rotary tiller is the perfect machine suitable for the minimum tillage system. The high degree of pulverization does make rotary tillers good seedbed preparation. Rotary tillers are also good for cutting up vegetable matter and mixing it throughout the tilled layer. Rotary tillers are widely used for rice in Japan (Kawamura, 1970) and other Asiatic countries. Rice paddies in these countries are often "puddled" by means of underwater rotary tillage. The rotor usually rotates in the same direction as the tractor wheels. Each blades cuts a segment of soil as it moves downward and toward the rear as shown in Fig.4. Most rotary tillers make either 2 or 3 cuts per revolution. Because of the high peak torques developed during each cut, it is important to stagger the blades in the different courses, with equal angular displacement between them, so no two blades strike the soil at the same time.

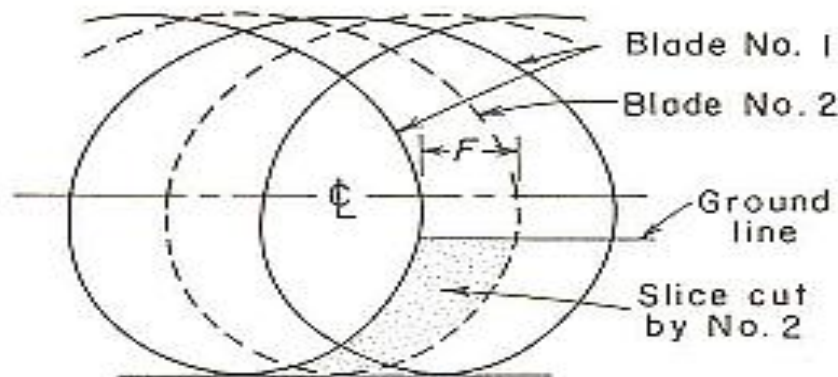


Fig. 4. Paths of cutting edges or tips for 2 blades 180° apart, in relation to forward travel (Kepner et al., 1977).

Tillage is an operation performed to obtain a desirable soil structure for a seedbed. A granular structure is desirable to allow rapid infiltration and good retention of rainfall, to provide adequate air capacity and exchange within the soil and to minimize resistance to root penetration. Rotary tiller or rotavator (derived from rotary

cultivator) is a tillage machine designed for preparing land by breaking the soil with the help of rotating blades suitable for sowing seeds (without overturning of the soil). Nowadays, utilization of rotary tillers has been increased in agricultural applications because of simple structure and high efficiency for this type of tillage implements. By taking advantage of rotary tillers, the primary and secondary tillage applications could be conjugated in one stage. This results in a decrease in the number of machinery passes, causes a decrease in overall costs for land preparation.

When a tillage operation is performed with a rotary tiller in the field, the soil texture will be a function of soil conditions, blade geometry, blade kinematics and soil flow dynamics. As the blades of a rotary tiller rotate, each point on a given blade traces a trochoidal path in the soil. On the forward part of the trochoidal path, the blade will cut or fracture untilled soil and on the return part of the trochoid, the blade will tend to mix and pulverize the soil slices (Kinzel et al., 1981).

Tillage is the manipulation of soil by mechanical forces. The purpose of tillage tool design is to create a mechanical system, that is, a tillage machine or a series of machines capable of controlling the applied forces in order to achieve a desired soil condition (Gill and Vanden Berg, 1967). Gill and Vanden Berg also have emphasized that mathematical description of a tillage process can be accomplished only when all the elements of the process are expressed in a quantitative sense. The goal of tool design is to optimize the function, efficiency, and economy of the tillage process. True engineering design cannot be achieved until analytical relationships, based on scientific principles, are available (Ros et al., 1995).

Rotary tiller, as an active tillage tool, uses a power driven rotor to replace the conventional tillage implements. It can achieve advantages in terms of its lower draft requirement, better soil breakup and more efficient inversion and trash mixing. When a tiller is pulled through a field, the resulting soil texture will be a function of soil conditions, blade kinematics, and soil flow dynamics (Jafar & Singh, 2009). The power consumed, cutting action, the blade geometry, the path and the orientation of the blade relative to the path of the cutting edge of the blade will influence soil texture and cultivation. The path of the cutting edge is a function of perpendicular distance from the cutting edge to the rotor axis of rotation, the rotor velocity and forward velocity of the machine (Kinzel et al., 1981).

3. Previous work on rotary tillers blade

As already discussed in the preceding section 1.0 that rotavator may have 'L' shape, 'C' shape, 'J' shape, hook tines and straight knife blades to suit various Indian conditions. But generally, L-shaped blades are used mostly in Indian rotavator. Accordingly a lot of work has been done on this subject particularly to develop blade kinematics, modeling of blade, matrix equations etc. These are described in this section.

The matrix equations for describing the motion of the blade of rotary tiller were described by Kinzel et al., (1981). These equations were used for graphical representation of an arbitrary blade cross-section to show the relative motion of the blade with respect to the trochoidal path of the cutting edge. This method was used to study the effects of changes in rotor and translational velocities and in blade orientation angles.

Chen et al., (1993) demonstrated that energy consumption in rotary tillage can be decreased through improved blade design.

Beeny and Khoo (1970) developed three blade shapes with different radius of curvature (C-shape, I-shape and L-shape). They reduced the cutting force by reducing ratio of blade surface contact with soil to volume of soil cut by the blade. They also compared the performance of optimized rotary blades in the basis of specific work. The specific work requirement of the L-shape blade was found comparatively higher than the other two types over a similar range of operating conditions.

The parameters of rotary tiller blades were studied with the view of decreasing energy requirements by Lukyanov (1978). The design of the cutting element and the mounting on the rotor should guarantee free movement of the soil being cut loose. It was found that decrease in the speed, angle of cutting, and length of the forward face of the blade reduced energy requirements.

Sakai (1978a, b) mentioned that rotary tools of rotary tiller were equivalent to the share and mouldboard of plough and use of rational shape of rotary tool was indispensable for effective tillage. It was found that the external soil forces, i.e. driving forward force and lifting up force were presumed to be affected by the radial suction force of the blade which was caused by the shape of the scoop surface of the blade and by the knife factor which depended upon the shape of knife edge.

Gupta and Visvanathan (1993) by developing a mathematical model for a rotary blade in saturated lateritic sandy clay loam soil, found that the energy requirement of a rotary tiller consist of 0.34–0.59% for cutting soil slice, 30.5–72.4% for throwing out soil slices, 0.96–2.45% for overcoming soil–metal friction, 0.62–0.99% for soil–soil friction and 23.1–64.6% for idle power. A mathematical model was developed to predict the energy requirement for the combined effect of a disc plow and a rotary blade in clay soil suitable for wet rice cultivation in Malaysia by Ahmad and Amran (2004). The validity of the model was also checked via experiments. They found that the model can be used to improve the machine capabilities for estimating energy requirement in soil manipulation. A study was carried out to measure the important design dimensions of both wet land (L-type) and dry land (C-type) rotary blades (Das and Mahapatra, 2005).

Hendrick and Gill (1978) made a theoretical analysis of the motion of the rotary tiller blade. Equations of motion were used to analyze the characteristics of the trochoidal path and an instant centre technique was used to determine the direction of motion and velocity at any point of the trochoidal path. A powered rotary chisel was designed and tested by Hendrick (1980). A low rotary speed and forward rotation was kept to reduce the draught and power requirement. Based on the selected values of velocity ratio, the under sides of the blades were designed so that they would not contact uncut soil (Hendrick & Gill, 1974).

Sakai (1978) described the design theories of the Japanese C-shaped rotary tiller blade. The design process based on it produced satisfactory results. Thakur and Godwin (1991) observed that the peak resultant force occurred after 10–15 degrees of penetration of the blade tip and the blade traversed a circular trajectory in quasistatic condition. Singh (1996) found that the tools of the 'L' and 'C' shapes consumed minimum specific energy in comparison to other conventional rotary tillage tools.

Noguchi et al. (1992) developed an expert computer aided design (CAD) system for determining the arrangement of blade on a rotary cultivator. The system includes a database that contains 17 different blade configurations for a cultivator with 24–56 blades. Ros et al. (1995) developed a computer program to design and display selected passive tool shapes. The tool surface was represented by a multiplicity of quadrilateral faces limited by user selected bounding curves. The (x, y, z) face coordinates were generated by a FORTRAN program and read into AutoCAD using an AutoLISP program. The method permitted a complete study of the influence of the geometrical parameters upon the final soil condition and energy requirement.

Saimbhi et al. (2004) used coordinate transformation to simulate the kinematics of a rotary tillage, C type blade. Using three dimensional computer graphics, a Bezier surface of the rear surface of the blade was generated and error was found out. The soil-blade interaction was analysed using a scan of trochoidal paths of the leading and trailing edges of the blade (LT scan) computer programmed in language C/C++. Interference of the trailing edges of the blade with uncut soil was eliminated by design changes and checked with LT scans for the range of selected rotor speeds and forward speeds. The rectified surface was manufactured using high carbon steel.

Lee et al. (2002) investigated the effects of rotary blade shape, rotational direction, number of rotary blades around the periphery, with and without soil-cutting disc blades on soil break up and torque requirements. They used three different types of rotary blade to study the strip tillage characteristics for use in dryland direct rice seeder.

Salokhe and Ramalingam (2003) conducted experiments in a Bangkok clay soil to evaluate the performance of a rotary tiller equipped with reverse or conventional C-type blades. Tests were conducted on wet land as well as in dry land to calculate the power-take-off (PTO) power consumption from the PTO torque and speed. The results indicated that the PTO power consumption was less for the reverse-rotary tiller compared to the conventional tiller for all passes and forward speeds.

Shibusawa (1993) reported a remarkable reduction of specific power demanded by an up-cut rotary tiller as a function of blade configuration. In this study, he observed the dynamics of the rotary tiller tilled-soil and the blade kinematics and noted tremendous amounts of re-tillage occurring as the depth of tillage increased. He surmised such re-tillage to be the main source of high energy expenditures associated with deep rotary tillage. From the observations, Shibusawa hypothesized that significant reduction in energy and power requirement for deep tilling rotary tiller can be realized if re-tillage could be avoided.

The performance of a rotavator equipped with uncoated and enamel-coated blades was evaluated by Salokhe et al. (1999) in clay soil at an average soil moisture content of 21.6% (db). They compared power requirement and quality of work for uncoated and enamel-coated blades and found that maximum saving in power of 22% was obtained at 1.5 km/h speed during the first pass of enamel-coated blades compared to that of

uncoated one. They also observed that the rate of wear of enamel-coated blades was less than that of the uncoated.

Niyamapa et al. (1994) determined the optimum parameters for the design of a rotary cultivator in a laboratory study in a soil bin with clay soil at a moisture content of 23.26% (dry basis) and a dry bulk density of 1.29 g/cm³. They studied the power requirement for cutting and throwing the soil and found that there is an increase in power requirement with the increase in rotor speed, forward speed, and tilling depth at a given width of tiller. They found the optimum design parameters of a rotary cultivator with a tillage depth of 18 cm at a forward speed of 0.35 m/s and rotor speed range of 165-220 rpm. At these operating conditions power consumption was 2.70-3.50 kW. Singh (1996) found that the tools of the 'L' and 'C' shapes consumed minimum specific energy in comparison to other conventional rotary tillage tools.

The proper design of the interrelated cutting and clearance angles of rotary tiller blades is essential to efficient operation. As the effective cutting angle is increased from some minimum value, the power requirements of the tiller and the amount of soil pulverizing, throwing and mixing are increased. Hence, there is need to study the blade characteristics of rotavator most commonly use in specific Indian region.

4. Tillage tools and energy

Tillage tools direct energy into the soil to cause some desired effect such as cutting, breaking, inversion, or movement of soil. Soil is transferred from an initial condition to a different final condition by this process (Ros et al., 1995). Tillage is a major operation for seedbed preparation and is one of the largest material handling operations. It is one of the major items of energy and cost expenditure in crop production (Saimbhi et. al., 2004). The energy input in soil manipulation is exceeded only by the level of energy input in irrigation (Singh, 1983). Thus, increasing the effectiveness of tillage tools, even by a small fraction, would amount to a huge saving in energy. It would be rather more economical to increase the productive rate of each machine rather than to increase the number of machines indiscriminately. Most of the tillage and soil engaging tools in use have been developed on the basis of experience and inventiveness. A number of inherent advantages of machines, which transmit power directly to the soil require that they considered as alternatives to tools drawn through the soil (Hendrick & Gill, 1971).

The increase in energy requirement occurs when the trailing edge of the blade presses into the uncut soil, a tendency of the tiller to 'walk out' of the soil and to cause undue compaction of the uncut soil. Depending on the soil conditions, blade geometry and velocity ratio, the interference of the underside of the blade and the uncut soil may result in severe soil compaction and high power consumption. This is the main cause of vibrations, which are a result of the reaction of soil upon the tiller blades. The proper design of the inter-related cutting and clearance angles of rotary tiller blades is essential for an efficient operation. As the effective cutting angle is increased from some minimum value, the power requirements of the tiller and the amount of soil pulverizing, throwing and mixing are increased (Hendrick & Gill, 1974).

In maize and spring barley production systems in combination with a chisel plow, rotary tillers have been found to have high energy requirements, but rotary tilling is more effective in saving labor compared to conventional tillage systems (Kosutic et al., 1994).

There are several advantages of a mathematical formulation of tillage tool geometry. A desired shape may be described exactly in terms of a relatively small set of geometrical parameters. Modifying such a shape becomes a rational process of adjusting these parameters. Manufacturing of a given shape should be much simplified because the geometrical information used in the design and visualization could be easily transferred to a numerically controlled machine tool. The method permits a complete study of the influence of the geometrical parameters upon the final soil condition and energy requirements (Ros et al., 1995).

The increase in energy requirement occurs when the back surface of the blade presses into the uncut soil, a tendency of the tiller to 'walk out' of soil and undue compaction of the uncut soil. Depending on the soil conditions, blade geometry and velocity ratio, the interference of the backside of the blade and the uncut soil may result in severe soil compaction and high power consumption. This is the main reason to cause vibrations, which are a result of the reaction of soil upon the tiller blades (Mahal et al. 2012).

5. Discussion

As discussed in the preceding sections, it has been understood that most of the works done related to modeling, configuration, surface treatment etc. of different rotary blades, which are most commonly used in either Japan, Thailand or in Europe and the types are Japanese C-shaped blade, the European L-shaped blade and the European C-shaped blade. It has also been reported that the shape of the rotary blade is an important factor that influences its power requirement, torque characteristic and the specific energy requirement. Although some work has been done to identify the blade wear through experimentally and field trials. Based on the results, some materials different from the commonly used one, has suggested through material characterization, but these immense extra cost which ultimately increase the farming operational cost. No work has been reported to optimize the blade design to reduce the impact force, stress on cutting edges, wear and the specific tilling energy for Indian 'L' type narrow blade in specific Indian region. Design optimization of rotary tillage tool has been done in some work along with total structural analysis of the rotary tiller in relation to the overall geometry, but not addressed the optimized design for the blade.

6. Conclusion

However, from the above stated review and discussion it has observed that the rotary tiller blades interact with soil in a different way than normal plows and due to this blades are subjected to fatigue and wear. The continuous fluctuating impact of soil crust / clods / stone develops high stress areas on blade tip or blade critical edges. So these stresses and blade wear needs to be minimized. One of the ways is the material characterization of blade but these impose extra cost which, ultimately increase the farming operational cost. So there is a need for development of suitable blade from commonly used material like high carbon steel etc. through design optimization of geometric configurations or geometric parameters so that the blade will be able to withstand all stress /loads coming on the cutting edges and thereby increase the service life.

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