these given parameters, the design draft requirement, R for the implement becomes 1,500 N. Therefore, the implement working resistance is 1,500 N. The power unit has enough draft to power the implement given the calculated maximum implement available pull of 3,147 N versus the implement working resistance of 1,500 N.

C. Design in SOLIDWORKS

SOLIDWORKS 2017 software was used to develop computer-aided design (CAD) drawings and finite element method (FEM) for the strength analysis of the implement (**Fig. 3**). The weeder in **Fig. 3a** simply scraps the weeds outward creating a weed-free planting strip (**Fig. 4i**). An adapter was designed to incorporate a precision planter onto the weeder frame. Components of a planter (given in **Fig. 2d**) are incorporated to a weeder in **Fig. 3a** into a weeder cum planter shown in **Fig. 3b**. Components borrowed from the precision planter include hoppers (for both fertiliser and seed), tine (for fertiliser furrow opening), double disc (for seed furrow opening), seed and fertiliser metering devices. After crop emergence, the discs are set facing inwards (**Fig. 3c**), it removes weeds by scrapping the soil towards the crop.

D. Strength analysis of the weeder

The weeder components were subjected under combined tension, shear, bending and torsion loading in SOLIDWORKS simulation. The following seven steps were taken in the process; Step 1: Enabling SOLIDWORKS Simulation by checking the SOLIDWORKS simulation boxes in Add-ins; Step 2: geometry creation of the part to be analysed in FEM. The study was created for each part for static equilibrium of the part under study; Step 3: Material property assignment: This is done to assign material to the component under simulation; Step 4: boundary condition specification to define the restraints and loads (external forces); Step 5: mesh generation to discretise the part into elements; Step 6: running the simulation to obtain the results of the analysis. The detailed simulation report are provided in Appendices.

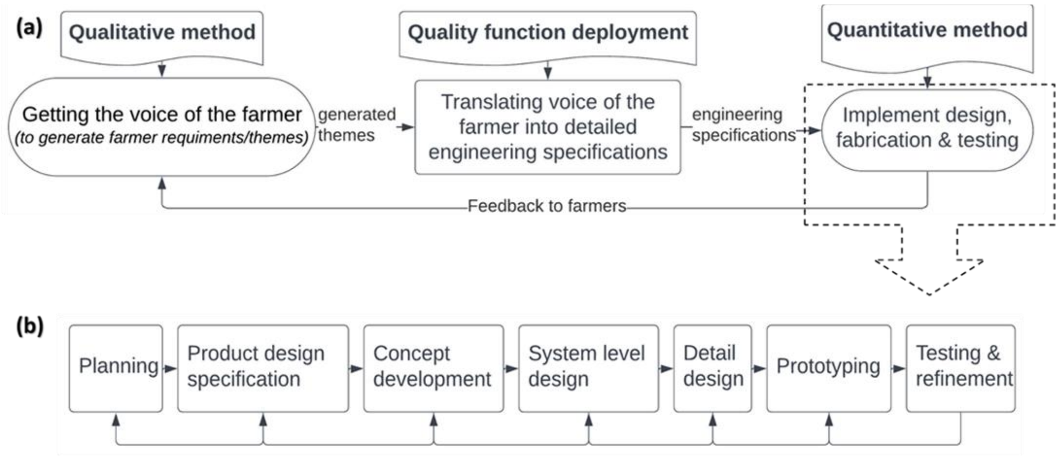

Fig. 1: Research Design Flow chart: Quality Function Deployment (a); Product development process (b).

Fig. 2: Option of soil engaging components: Animal draft cultivator (a) [1]; Disc plough (b); Rotovator (c); Precision planter (d).

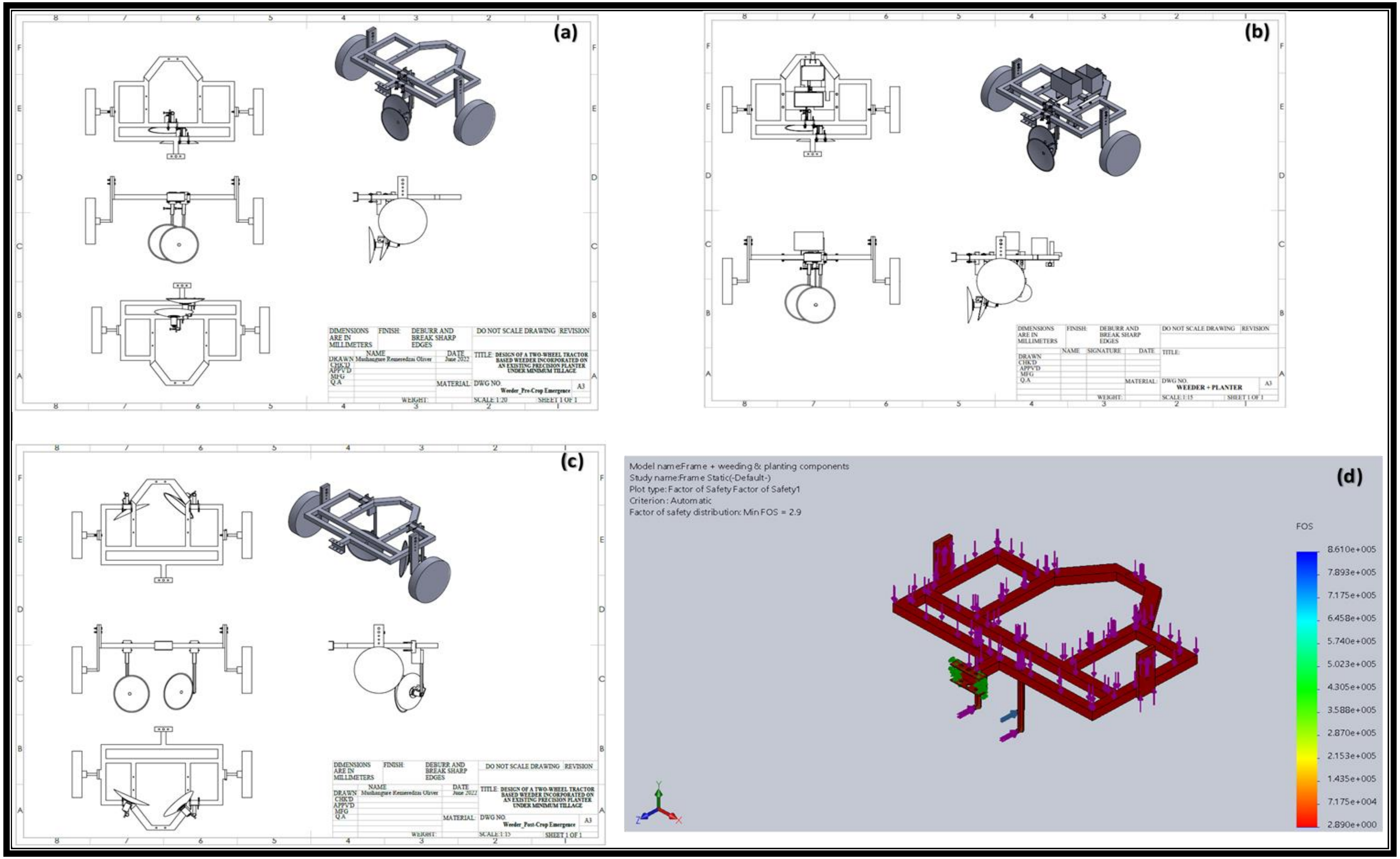

Fig. 3: SOLIDWORKS assembly drawing for (a) weeder before crop emergence; (b) weeder incorporated with a precision planter; (c) weeder after crop emergence and (d) simulation for minimum factor of safety when subjected to all forces.

E. *Prototyping*

Prototyping was done based on the results from the detail design phase. The developed implement does three main functions, namely, weeding before planting; simultaneous weeding and planting; and weeding after crop emergence. **Fig. 4** shows the stepwise assembling of fabricated components. **Fig. 4a** shows the disc arrangement for scrapping of weeds outward leaving a clean weed-free surface before planting. The tilt and disc angles are adjustable to suite various angle combinations for different weeding requirements as shown **Fig. 4** (**g** and **h**, respectively). Tests were conducted on various tilt and disc angle combination for the best performance of the weeder. **Fig. 4c** shows the mounting of an adapter to the weeder frame for incorporation of planter components so as to combine weed removal and planting into one when introducing a second crop in the case of relay intercropping. Fig. 4d shows mounting of planter components, **Fig. 4e** showing a complete weeder incorporated with a planter. **Fig. 4f** shows the weeder with discs set facing inwards for weeding after crop emergence.

F. *Testing of 2WT weeder*

1) *Laboratory test*

Laboratory test was done to determine whether the implement settings are adjustable to meet the desired field test such as angles (tilt and disc angle), cutting depth, width of cut. During the laboratory tests, minimum and maximum attainable setting measurements (for angles, depth and width) were determined. The depth and width were measured using tape a measure, angles were determined by Pythagoras theorem.

2) *Field test*

The weeder field tests were conducted after laboratory test to observe the performance of the implement if it satisfies the farmer needs. The weeding implement prototype was tested against the design specifications which are: (1) field capacity (hr/Ha), (2) quality of weeding and (3) fuel consumption. The experimental design was comprised of two treatments, which are: T1 = Weeding clearing and planting in two operations, and T2 = Combined weeding clearing and planting in one operation.

The designed weeder has two weeding functions which are (1) before planting and (2) after crop has emerged. These two operations are achieved by setting the weeder differently. Before planting, the weeding discs are set to face outwards The discs are set to superficially scrap the surface to a weeding depth meeting conservation tillage practices of less or equal to 5cm. The scrapping operation moves the soil, weeds and mulch outwards leaving a scrapped surface free of weeds ready for planting. The scrapping is only done where the crop is to be planted, with a scrapping width of not more 45 cm. Weeding operation after crop emergence is achieved by reversing the two discs to face inwards, unlike before planting. With this arrangement, the two discs will be scrapping the soil, weeds and mulch inwards towards the crop (light ridging).

a) *Quality of weeding*

Quality of weeding was quantified in terms of weeding efficiency and plant damage from the experimental plots. Weeding efficiency is the ratio of the number of weeds removed by the weeding implement to the number of weeds present per unit area expressed as a percentage. The samplings were done by quadrant method, by randomly selecting spots of 1 square meter [29]. Weed control efficiency was determined at various disc angles at a set depth of cut using **equation 4**.

$$\eta\text{weeding } (\%)=\frac{W_1-W_2}{W_1}\times 100 \qquad (4)$$

Where, W_1 = Number of weeds counted per unit area before weeding operation; W_2 = Number of weeds counted per unit area after weeding operation

Plant Damage represented as PD in **equation (5)** is the ratio of the number of plants damaged after operation in a row to the number of plants present in that row before operation expressed as a percentage.

$$\text{PD } (\%) - \left(\frac{q}{p}\right)\times 100 \qquad (5)$$

Where, p = Number of plants in a 10 m row length of field before weeding; q = Number of plants in a 10 m row length of field after weeding.

b) *Fuel consumption*

Displacement method was used to measure fuel consumption by replacing the fuel tank with a measuring cylinder. The measuring cylinder is filled to a known measured value (L_1) before running the trial and read off the new value (L_2) after trial run. The fuel displaced (L_1-L_2) is recorded as the fuel consumed for the test duration and weeded area in litres per hour and litres per hectare, respectively.

Fig. 4: Assembly process. (a) discs set facing outward for scrapping weeds before planting; (b) weeder set for weed crapping; (c) mounting of an adapter to incorporate planter components; (d) incorporation of planting components i.e. hoppers, seed metering, tines and discs on the adapter plate; (e) complete weeder incorporated with a planter; (f) discs set facing inwards for weeding after crop emergence; (g) setting of tilt angle; (h) disc angle; (i) weed-free planting strip.

IV. RESULTS

This section reports on qualitative data generated from farmer interviews and quantitative data collected in laboratory and field experiments, and analysed in IBM SPSS 27 statistical software.

A. Qualitative results and Data analysis

A qualitative analysis was conducted to understand how weeding was being done and getting farmers' views and expectations. The interview was conducted to 2WT owners under the SIFAZ project who offer small scale mechanisation services to other farmers using a service provision model. Service provision model is a model whereby one offers a service for a fee, where not every farmer should own a piece of equipment in order to maximise capacity utilisation of equipment. The SIFAZ project has eighteen service providers (SPs) across Zambia, only seven (6 male and 1 female) were sampled from Monze and Mazabuka districts of Southern province. Certain details of the interview are shown in **Table II**.

Table II. Interview responses

Interview Question	**Response**
Farm power reliance	The 2WT SPs also rely on both ADP and 4WT
Farming practice	85.71% practice CA and 42.86% practice CP
Weeding challenge	All the respondents cited weeding as the main challenging operation for different reasons including limited weeding tools, labour unavailability during peak labour demand.
Weeding methods	All the respondents are still using hand hoe manual weeding methods and only 14% also use herbicides.
Type of labour	About 86% of interviewees use family labour and 43% hire weeding labour.
Appropriateness of 2WT	The participants are satisfied with the appropriateness of the 2WT as an affordable farm power source for the small scale farmers.
Any 2WT weeding implement?	They have a wide range of 2WT implements, except a 2WT powered weeder, which is not currently on the market
Suggested weeding work rate of a 2WT weeder	Respondents also suggested the field capacity for the 2WT weeder to fall between one to 2 days per hectare to replace hand hoe weeding with work rates of about 7 person-days per hectare

B. *Two-wheel Tractor Weeder Test Results*

1) *Implement Laboratory Test*

Laboratory test was done to determine the possible implement settings for trial in the field experiments. The laboratory exercise established the minimum and maximum field test measurements and are provided in **Table III.**

Table III: Laboratory measurements

Variable	Magnitude
Width of cut	15 cm to 45 cm
Disc angle	0 cm to 90 cm
Tilt angle	0 cm to 90 cm

2) *Angle optimisation*

An experiment was conducted to determine the optimum tilt and disc angle with respect to field capacity, fuel consumption, weeding efficiency and plant damage. The data failed to meet the ANOVA assumption, a nonparametric test for two or more independent samples was conducted so as not to violate the outlier, normality and homogeneity assumptions.

a) *Nonparametric Independent-Samples Kruskal-Wallis Tests*

The Nonparametric Independent-Samples Kruskal-Wallis Test was conducted at 95% confidence interval to determine the effect of tilt and disc angles on the parameters presented in **Table IV**.

The **Fig. 5**, shows plant damage in relation to tilt and disc angle. According to the hypothesis (**Table IV)**, there is no significant difference of plant damage across tilt and disc angle. Tilt and disc angle have a significant effect on the weeding efficiency with the highest efficiency on tilt-30° and disc-31° (**Fig. 5b**). Fuel consumption is significantly affected by tilt and disc angle with tilt-30° and disc-31°, being the most conservative with lowest fuel consumption (**Fig. 5c**). Tilt and disc angle also affect the field capacity significantly with tilt-30° and disc-31°, achieving the best work rates (**Fig. 5d**). The tilt-30 and disc-31 was found to be the optimum combination of angles for the following reasons.

Table IV: Hypothesis Test Summary

#	Null Hypothesis	Test	Sig.^{a,b}	Decision
1	The distribution of Plant Damage (%) is the same across categories of Tilt and Disc angle.	Independent-Samples Kruskal-Wallis Test	.374	Retain the null hypothesis.
2	The distribution of Weeding Efficiency (%) is the same across categories of Tilt and Disc angle.	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis.
3	The distribution of Fuel Consumption (L/Ha) is the same across categories of Tilt and Disc angle.	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis.
4	The distribution of Field Capacity (Hrs/Ha) is the same across categories of Tilt and Disc angle.	Independent-Samples Kruskal-Wallis Test	.001	Reject the null hypothesis.
5	The distribution of Width_m is the same across categories of Tilt and Disc angle.	Independent-Samples Kruskal-Wallis Test	.002	Reject the null hypothesis.

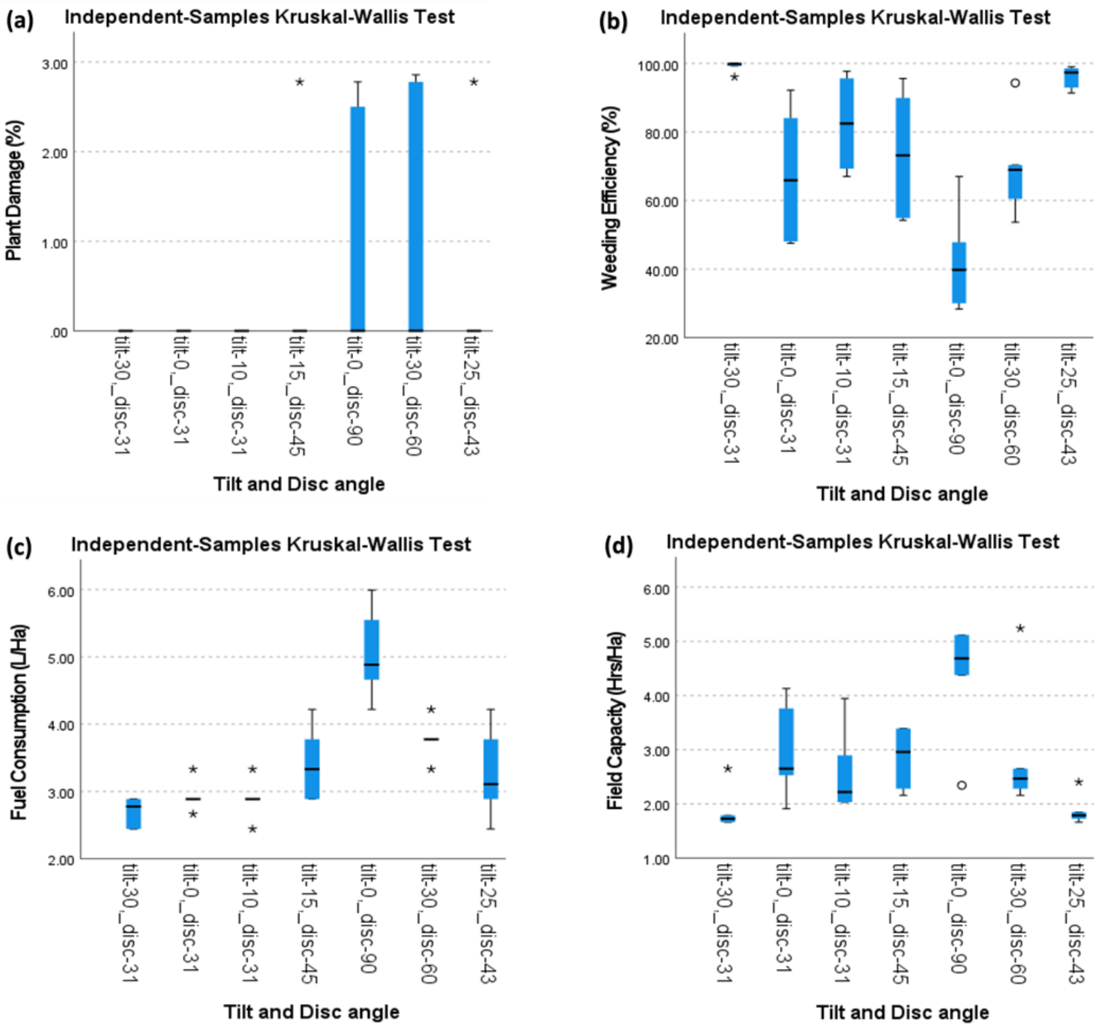

Fig. 5: Two wheel tractor weeder performance. (a) Plant Damage across Tilt and Disc angle; (b) Weeding Efficiency across Tilt and Disc angle; (c) Fuel Consumption across Tilt and Disc angle; (d) Field Capacity across Tilt and Disc angle.

V. DISCUSSION

Weed infestation is one of the top most challenging operation in agriculture with about 62% and 43% of farmers in Zambia and Zimbabwe, respectively, facing labour famine during weeding [30]. In manual CA production systems, the demand for labour for the preparation and weeding of the land is much higher than in conventional production systems [31]. There is a lack of consideration for labour issues emanating from the perception that labour in smallholder systems of Southern Africa is abundant and thus non-limiting [32]. This notion is also fuelled by macroeconomic analyses such as the land : labour ratio [33], which are based on national data that may be too aggregated to reveal farm-level dynamics [34]. Several lines of evidence point to the fact that labour and farm power are increasingly becoming the main limiting factors to the productivity of smallholder systems in Southern Africa [35] and probably a significant constraint to the adoption of sustainable intensification technologies (which are labourious). Most young and middle-aged farmers are migrating to towns resulting in labour famine in rural areas [36]. The most common hand hoe weeding used among smallholders has a mean labour of 13.83 man-days/hectare (110.64 person. Hours/hectare) per weeding operation [37].

Intercropping is a vital practice in the cropping system to sustainably improve land utilisation and increase productivity. However, intercropping systems have many huddles, including labour deficiency [36]. Precision management and close attention to weed control must be solved for cereal and legume intercropping producers [38]. Utilization of agricultural machines that are appropriate for this model would greatly increase labour productivity [36; 39]. There is a need to develop appropriate machinery and tools for mechanical weed control beyond herbicides, cultivators, and hand hoeing to address labour bottlenecks and assess the most cost-effective method to control weeds [30].

VI. CONCLUSION AND RECOMMENDATIONS

A. *Conclusions*

This study aimed to develop a 2WT-based mechanical weeding implement under minimum tillage agriculture incorporated with a precision planter. The main objective was broken down into more achievable specific objectives. The 2WT weeding implement was designed to meet the reduced tillage requirements of weeds being scraped shallowly to a weeding depth of less than 5 cm. An adapter was developed to attach a precision planter onto the weeder to synchronise weeding and planting operations at the same in a single pass. The weeder cum planter was fabricated and the performance of 2WT weeder was determined through laboratory and field experiments. Combined 2WT weeding and planting operation that was done in a single pass compared to weeding and planting individually in two passes showed an improvement in field capacity and fuel consumption by 93% and 88%, respectively.

B. Recommendations

The development of a 2WT weeder from existing plough discs provided with tractors presents promising results. Manufacturers and suppliers of 2WT-based equipment are encouraged to explore this innovation. The simplicity of this development, derived from the 2WT disc plough and precision planter already on the market, allows for versatility as a plough, weeder, and cum planter with minimal additional accessories. Collaboration between the Ministry of Agriculture Extension Services and the manufacturing industry is crucial to generating demand and awareness for reduced tillage innovations. These innovations not only reduce production costs but also enhance operational efficiency. Small-scale farmers, in particular, require more weeding options. Therefore, there is a pressing need to create awareness of available weeding alternatives suitable for adoption by small-scale farmers and service providers. Given that most small-scale equipment, including precision planters and ploughs, are imported, promoting local manufacturing with considerations for appropriate material selection is essential. Local manufacturing not only supports the economy, but also improves access to spare parts, contributing to the sustainability of agricultural practices.

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