Contents available at: Sri Lanka Journals Online

Tropical Agricultural Research

Journal Home Page: https://tar.sljol.info

RESEARCH

Impact of Motorized Tea Harvesters on Tea Yield and Yield Determining Parameters

S.R.W. Pathiranage[1]*, M.A. Wijeratne[1] and W.A.J.M. De Costa[2]

[1]*Agronomy Division, Tea Research Institute of Sri Lanka*
[2]*Faculty of Agriculture, University of Peradeniya, Sri Lanka*

ARTICLE INFO

Article history:
Received: 11 August 2023
Revised version received: 31 August 2023
Accepted: 13 September 2023
Available online: 01 October 2023

Keywords:
Impact on tea yield
Mechanical tea yield decline
Motorized tea harvesters
Tea yield determinants

Citation:
Pathiranage, S.R.W., Wijeratne, M.A. and De Costa, W.A.J.M. (2023). Impact of motorized tea harvesters on tea yield and yield determining parameters. Tropical Agricultural Research, 34(4): 316-330.

DOI:
http://doi.org/10.4038/tar.v34i4.8672

Pathiranage, S.R.W.
https://orcid.org/0000-0003-3780-1736

ABSTRACT

Motorized tea harvesters vary in shoot cutting & collecting mechanisms and reported considerable yield decline in Sri Lanka. In this study, three non-selective harvesters were used to evaluate the impacts of different cutting & collecting mechanisms on tea yield-determining parameters compared to manual harvesting (control). The machines used were battery-operated Forbes & Walker harvester with helically arranged picking arms (BatFW), battery-operated Kawasaki harvester with reciprocating blades (BatKW), and petrol-driven Kawasaki harvester with reciprocating blades (PetKW). Tea yield, coarse leaf content, operational time, shoot compositions, branch girthing, and root starch content were recorded for one year. The motorized harvesters reduced tea yield by nearly 50% compared to the control. The number of machines required (units/ha/day) were 6, 4 and 2 for BatFW, BatKW and PetKW, respectively, as compared to eight manual pluckers and the corresponding land extents covered were 0.17, 0.25 and 0.47 (ha/unit/day), as against 0.13 in manual. Manual harvesting and BatFW consumed comparable higher worker requirements than the others. The average shoot weight and shoot density were the least affected by BatFW. The highest immature (arimbu) shoot removal was by PetKW. The highest dormant shoot accumulation in the plucking table was by BatFW. Reciprocating blades harvested more productively (700 g/cm/day) than picking arms (500 g/cm/day). All machines affected branch girthing and root starch reserves compared to manual harvesting. The mechanical impacts on yield determining parameters viz., immature shoot removal, accumulated dormant shoots, affected yield components, poor branch development, and depleted root starch reserves collectively resulted the tea yield reduction.

*Corresponding author- sampathir2002@gmail.com

INTRODUCTION

Harvesting of tea is a highly labor-intensive and costly operation (Ravichandran and Prathiban, 1997; Wijeratne, 2003), and accounts for 60-70% of the total field worker requirement, and 35-40% of the total cost of made tea production (Goldsmith and Kilgour, 1999; Wijeratne, 2003 & 2012; Madamombe *et al.*, 2015). The adoption of correct harvesting policies significantly influences the productivity and profitability of tea plantations. Generally, labor requirement for manual harvesting ranges from 10 to 12 Laborers Per Hectare (LPH).

The majority of tea lands in Sri Lanka are harvested manually leaving immature shoots (*arimbu*), which are important to ensure a sustainable tea yield. The two main methods of manual harvesting are, mother leaf harvesting (light harvesting) and fish leaf harvesting (hard harvesting). Mother leaf harvesting adds leaves to the plucking table (surface) and forms a layer of mature leaves at the top (maintenance foliage). Fish leaf harvesting (hard harvesting) removes all normal leaves and gives a higher yield in the early stages, but prolonged hard harvesting affects sustainable shoot growth (Tanton, 1979; Visser, 1960; Wijeratne, 2001; Wijeratne and Watson, 2015). Therefore, the adoption of both fish leaf and mother leaf harvesting alternately in rainy and dry weather during the year adds an adequate number of leaves to the maintenance foliage while maximizing yield (Wijeratne, 2001).

The scarcity of workers in the tea industry is an alarming problem with a 57% decline in the workforce from the level that is required. This is especially severe in low-country estates (Samansiri *et al.*, 2011; Shyamalie *et al.,* 2016). Young workers have shifted from the tea sector to other industrial sectors due to better education, better opportunities, low wages in the tea sector, rapid social development (Modder and Wijeratne, 2002; Wijeratne, 2003), and poor housing (Chandrabose, 2015).

Being the most labour-intensive field operation, manual harvesting is so highly affected by labour scarcity that extension of the harvesting interval is very common. This reduces the number of shoot generations over a given period (Wijeratne, 2003; Nayasulu, 2006; Madamombe *et al.,* 2013) and leads to a reduction in shoot density, and finally reduces tea yield (Wijeratne, 2012). Further, extended plucking rounds result in early dormancy (more *banji*) decreasing leaf quality drastically. Thus, extended harvesting intervals cause both qualitative and quantitative yield losses (Wijeratne, 2003).

In a labour scarce situation, mechanized harvesting of tea shoots can be done either by using shears or using motorized machines as alternatives to manual harvesting. Shear harvesting may be selective or non-selective depending on their type. Other mechanical tea harvesters at present are non-selective (Wijeratne, 2003; Pathiranage *et al.,* 2017 and 2018). There are different types of tea harvesters ranging from portable hand-held machines to large ride-on type machines, which are widely used in tea plantations in the temperate regions (*e.g.,* Japan, China) where tea bushes produce only 2-3 shoot generations because of the highly seasonal climate. In contrast, in Sri Lanka, the pattern of year-round rainfall and sunshine, along with less fluctuations in seasonal temperatures, result in an unsynchronized (continuous) shoot growth, which produces 5-6 shoot generations at different stages of development so selective harvesting becomes imperative. In selective harvesting, leaving immature shoots (*arimbu*) is essential to sustain a higher yield (Wijeratne, 2001; TRISL, 2003). In addition, a majority of the tea lands in Sri Lanka have a considerable slope (>10%), which makes the use of large-scale machinery impossible (Wijeratne, 2003; Pathiranage *et al.,* 2016). Drastic yield reduction due to continuous use of non-selective harvesting machines is due to the non-selectivity in harvesting and removal of maintenance foliage leading to the extension of harvesting intervals (Wijeratne *et al.*, 2000). Nevertheless, when machines were used only to manage the heavy cropping season, the yield loss could be maintained at a relatively lower level around 20-30% (Watson *et al.,* 1982; Wijeratne, 2003). To maintain the quality of the harvest obtained mechanically, the removal of coarse leaves should be done before supplying the tea flush to the factory.

Tea harvesting machines have three effects on the tea bush, *viz*., removal of immature shoots, removal of maintenance foliage and the higher severity of harvesting. They are believed to be the major contributory factors for the observed significant yield reduction. Immature shoots grow vigorously consuming much of the carbohydrates synthesized in the leaf canopy (Wettasinghe *et al*., 1981) and therefore, termed as a strong 'sink'. Mature leaves supplying carbohydrates are the 'source' (Visser, 1960; Krishnapillai, 1983; Manivel and Hussain, 1986; Wijeratne, 2001; Barman, 2005; De Costa *et al*., 2007; De Costa *et al*., 2009).

Motorized harvesters remove immature shoots (sink) indiscriminately (Bore and Ng'etich, 2000; Tea Research Foundation of Central Africa, 2007; Madamombe, 2008; Wijeratne, 2003 and 2012) disturbing the balance between the sink and source, reducing the number of shoot generations (De Costa *et al*., 2007), delaying bud break, and extending the shoot replacement cycle (Wijeratne, 2003). Thus, the average shoot weight is affected finally causing significant qualitative and quantitative losses in tea yield (Wijeratne, 2012).

Further, motorized harvesters extensively remove the maintenance foliage (Wijeratne, *et al.,* 1996; Wijeratne, *et al.,* 2000; Madamombe, 2013; Madamombe, *et al.,* 2015), and disrupt source - sink balance affecting photosynthesis causing a shortage of carbohydrates for growth and maintenance (Madamombe, 2008; Wijeratne, 2012). Moreover, the very high severity (very hard) of harvesting posed by machines (Wijeratne, 2003; Mouli, 2007) for prolonged periods results in reductions in tea yield, pruning weight, shoot weight, shoot density, maintenance foliage, root starch reserves, and frame development (Visser, 1960 and Wettasinghe *et al.,* 1981). Therefore, it could be hypothesized that the removal of maintenance foliage and higher severity could also be key reasons for the yield reduction reported in the motorized harvesting of tea.

In the past experiments conducted at the Tea Research Institute of Sri Lanka (TRISL), many aspects of mechanical harvesting have been tested such as different landforms, tea growing regions, planting systems (TRISL, 1998-2011), harvesting intervals, tea cultivars (TRISL, 1998-2003), harvesting methods (TRISL, 2009-2011), pruning systems, plant nutrients and intermittent and continuous use of machines (TRISL, 2005-2006). However, none of the above experiments were able to avoid the severe yield reduction caused by mechanical harvesting.

Despite the negative effects, tea growers are compelled to use motorized tea harvesters when they fail to maintain harvesting intervals properly with increasing severity of worker shortage. However, the motorized tea harvesters available in the local market are different from each other in their inherent technical characteristics such as cutting and collecting mechanisms, sizes, power sources and number of operators required. Although there is adequate scientific evidence on the effect of mechanical harvesting on tea yield and yield determining physiology in the tea bush, as described earlier, the influence of different cutting and collecting mechanisms have not been evaluated adequately. Therefore, the objectives of this study were to examine different cutting and collecting mechanisms of selected locally available non-selective tea harvesters, and determine their impact on tea yield and yield determining physiological factors, in comparison to manual selective harvesting.

METHODOLOGY

This experiment was conducted over one year at the St. Joachim Estate, Ratnapura, Sri Lanka (6°40' N, 80°23' E / 30 m *amsl* / >3200 mm yr^{-1}), using tea cultivar TRI 4042 in its second year in the pruning cycle. Three locally available motorized tea harvesting machines with different cutting and collecting mechanisms were selected for evaluation (Plate 1). The three harvesters selected were battery-operated F&W harvester with helically arranged picking arms (BatFW), battery-operated Kawasaki harvester with reciprocating blades (BatKW), and petrol-driven Kawasaki harvester with reciprocating blades (PetKW). All the harvesters were used at a 14-day harvesting interval. In the control treatment, tea shoots were manually harvested (Plate 1a) selectively at 7-day intervals leaving behind the small immature shoots known as *arimbu*.

The treatments were arranged in a Randomized Complete Block Design (RCBD) with four replicates.

Operating mechanisms of the motorized harvesters

The cutting mechanism of the battery-driven BatFW is comprised of "V" shaped blunt static metal teeth (blade length 20 cm) supported with helically arranged vertical picking arms (Plate 1b). Forward movement of the machine directs shoots into the valleys in the blade after which they are picked up by the arms. The same rotating action pushes harvested shoots into the cloth sack attached to the machine behind. The helical arrangement of picking arms minimizes pressure on the motor as it engages and picks a shoot(s) only from one valley at a time. The cloth sack rests on the plucking table. It is a lightweight (1.6 kg) small machine with a simple operation and can be operated easily by a single person.

The battery-driven BatKW (3.5 kg) has two vertically rotating flaps to direct shoots into the reciprocating sharp blades (length 30 cm). The rotating action of the flaps, guides the cut shoots into the cloth sack fixed behind. The leaf collecting sack rests on the tea bushes without any additional support. The machine has been designed to be lightweight and for simple operation by a single person. Both BatFW and BatKW are battery-operated and their batteries are held on the back of the operator (back-pack).

Fuel-driven (petrol) PetKW (4.5 kg) cuts tea shoots by the reciprocating action of sharp blades (length 60 cm) and shoots are air-blown into the collecting sack attached behind. Although this machine is designed for a single operator, it requires a helper to support and guide the leaf collecting bag with harvested leaves along the tea row especially on sloping terrain and in fields with shade trees. This harvester is powered by a knapsack type petrol driven two-stroke engine held on the back of the operator (back-pack engine).

All three motorized harvesters used in this experiment did not have any mechanism to select tea shoots based on shoot maturity. As such, they are non-selective harvesters, which remove smaller (<2 leaves) immature shoots and some maintenance foliage in addition to harvestable shoots. Therefore, the harvesting interval is extended up to about 14 days at low elevations depending on the growth of shoots as affected by climatic conditions.

Measurements

Fresh tea yield (g/plot), coarse leaf content (%), shoot compositions (on the plucking table and in harvested flush - count), girth of secondary branches (mm), % root starch reserves and time taken for harvesting operations were recorded over one year.

The harvest was sorted into acceptable shoots and coarse material (maintenance foliage), and weighed separately using an electronic balance (g/plot). The made tea yield was then calculated (kg ha^{-1} yr^{-1}) based on 21.5% outturn and 12,500 bushes ha^{-1} (Mohamed, 2003).

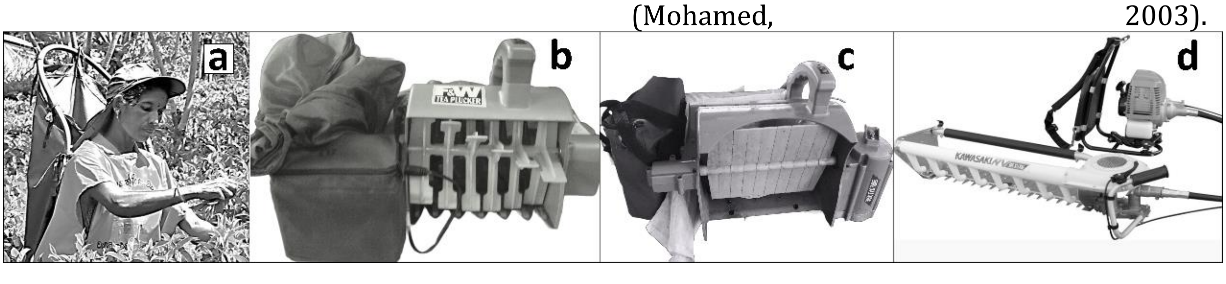


Plate 01: Treatments; (a) Manual, (b) Battery operated F&W harvester, (c) Battery operated Kawasaki harvester and (d) Petrol driven Kawasaki harvester

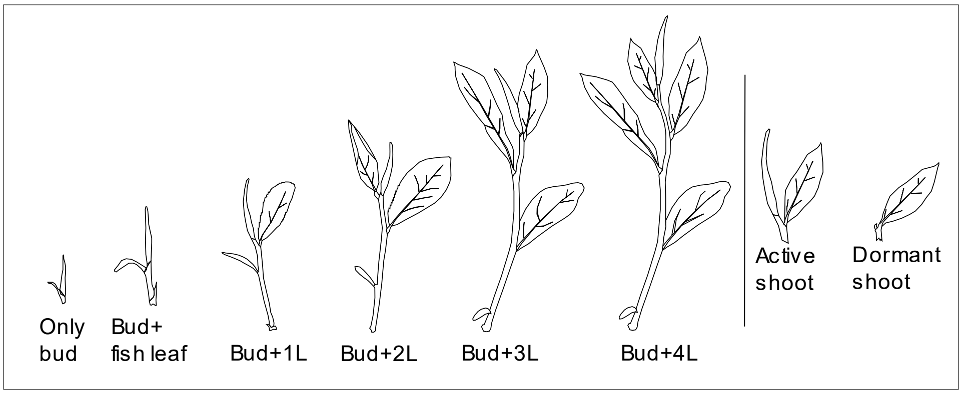


Figure 1: Graphical illustration of different shoot categories in a tea bush

At each harvest, the composition of the harvested crop [count and weight of each shoot generation (Figure 1) in undamaged shoots and weight of damaged shoots] was recorded by drawing a random sample of 100 g from the sorted (acceptable) shoots to represent the plot harvest. The average weight of a shoot and % of damaged shoots was then calculated.

Shoot composition (count) on the bush immediately before harvesting was also recorded as counts of shoots in each generation (Figure 1), *viz.,* Buds, Bud+Fish leaf (Fish), Bud+one leaf (1L), 2L, 3L, 4L, and dormant (*banji*) shoots, using a 30 x 30 cm quadrate.

Three secondary branches per plot were selected randomly and marked with lacquer paint at a point 1 cm above the base, where the girth was measured. Girths were separately recorded as diameter (mean of measurements from three angles) using a Vernier caliper at the beginning, 6 months, and 12 months after the commencement of treatment application. Gain in girth at 6 months and 12 months was then calculated as the difference compared to their initial measurements.

Hot-water-soluble root starch % (out of total carbohydrates) was measured three times during the experimental period at the beginning, 6 months, and 12 months after commencement of treatment application, in three randomly selected bushes per plot, following the analytical procedure described by Krishnapillai *et al.* (1992).

At each harvest, the time taken for the harvesting operation was recorded for each plot to estimate the labour requirement for harvesting per hectare (LPH) considering a tea stand of 12,500 bushes ha^{-1} and 6.5 working hours per day.

Data analysis

Data were analyzed using SAS version 9.1. Continuous data such as weights and heights were analyzed using the General Linear Models procedure with Analysis of Variance (ANOVA). Mean separation was done using the Least Significant Difference (LSD). Count and percentage data were analyzed with Categorical Data Analysis CATMOD and PROBIT procedures, respectively. The significance of treatment difference of measurements that were taken periodically on the same set of plants was tested using Repeated Measures (RM) ANOVA.

RESULTS AND DISCUSSION

Tea yield and coarse leaf content

All machines recorded significantly ($P<0.05$) lower tea yields, ranging from 46% to 54%, in comparison with manual harvesting (Table 1). However, tea yield did not differ significantly ($P=0.05$) among the harvesting machines, when they were used continuously throughout the year. Reciprocating blades (BatKW & PetKW) cut any plant part reaching their sharp blades, including immature shoots and maintenance foliage. In contrast, picking arms of BatFW randomly left some shoots due to their helical arrangement, which gave a misleading impression of being selective. But in reality, the BatFW harvesting mechanism was also non-selective as the shoots left on the plucking table were harvestable and should have been plucked. Further, those leftovers needed to be plucked in an extra pass of the machine, which decreased its worker productivity, as described elsewhere in this manuscript.

The coarse leaf contents (%) in the harvest varied significantly (P<0.05) among different machines (Table 1). The highest coarse leaf content was recorded by BatKW, followed by PetKW while BatFW gave the lowest. Manually harvested crops, however, contained negligible amounts of coarse materials (Table 1).

Selective manual harvesting did not add coarse leaves to the harvest, except by a mistake of the plucker. Although the vertically rotating picking arms of BatFW reported significantly (P<0.05) higher coarse leaf content compared to manual harvesting, it was significantly less than that of the other two harvesting machines (Table 1). Further, BatFW could maintain a low coarse leaf content mainly due to the vertically rotating action of the picking arms. Compared to PetKW, the narrower cutting width of the BatKW required a higher number of passes to harvest the entire area of the plucking table. In contrast, PetKW, covered the entire plucking surface in one or two passes. Thus, it is possible to have a higher percentage of coarse material collected by the BatKW than PetKW (Table 1). These coarse materials were removed by manual sorting before sending the harvest for processing. Due to less quantity of such coarse materials in the harvest, manual removal of coarse leaves was not a major issue with BatFW.

Shoot composition in the harvested crop

Average shoot weight

Average weights of harvested shoots by different harvesting methods are given in Table 2. The highest (P<0.05) average weight of a plucked tea shoot was recorded by the BatFW harvester and manual harvesting (Table 2). The Kawasaki machines (BatKW and PetKW), with horizontally reciprocating sharp blades, recorded the least shoot weights. The percentage reduction in average shoot weight compared to manual harvesting was approximately 15% - 16% for the two Kawasaki harvesters (Table 2).

Table 1: Variation in made tea yield and coarse leaf content under manual and mechanical harvesting over a period of one year [1]

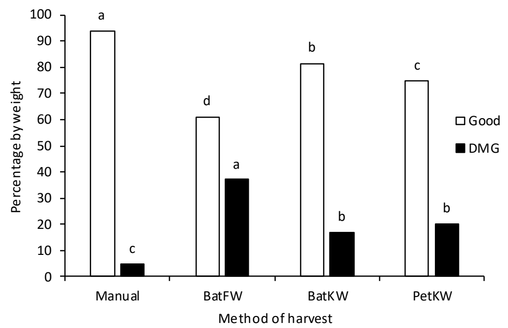
Treatment	Made Tea Yield (kg/ha/yr)	% Coarse Leaf
Manual harvesting	4296.2^{a} ±365.6	0.01^{d} ±0.33
Battery-operated F&W Harvester (BatFW)	2086.5^{b} ±139.9 (51%)	7.13^{c} ±21.8
Battery-operated Kawasaki Harvester (BatKW)	1974.9^{b} ±144.5 (54%)	14.84^{a} ±19.8
Petrol-driven Kawasaki Harvester (PetKW)	2297.2^{b} ±155.7 (46%)	11.67^{b} ±15.51
CV%	12.18	14.46

[1]*Means with the same letter in same column are not significantly different at* P=0.05*. Each mean is derived from four replicate plots.*

Table 2: Variation in the average weight of a harvested shoot as affected by different harvesting methods[1]

Treatment	Average shoot weight (g shoot^{-1})
Manual harvesting	0.97^{a} ± 0.035
Battery-operated F&W Harvester (BatFW)	1.07^{a} ± 0.031
Battery-operated Kawasaki Harvester (BatKW)	0.83^{b} ± 0.037
Petrol-driven Kawasaki Harvester (PetKW)	0.82^{b} ± 0.032
CV%	7.86

[1]Means with the same letter are not significantly different at p=0.05. Each mean is derived from four replicate plots.



Bars sharing the same letter(s) in each shoot category are not significantly different at P=0.05, Good = acceptable shoots for processing and DMG = Damaged shoots.

Figure 2: Variation in the percentage of good leaf (shoots acceptable for manufacture) and damaged shoots in the harvested crop.

Both Kawasaki machines share a similar cutting mechanism, which indiscriminately removes a considerable amount of immature shoots (Figure 3) and maintenance foliage (Table 1). Removal of the sink (immature/*arimbu*) and source (maintenance foliage) disrupts the balance between them causing a subsequent reduction in photosynthesis (De Costa, 2004). Moreover, reciprocating blades (BatKW and PetKW) harvest shoots with higher severity (deep cuts). Therefore, the low mean shoot weight of the crop harvested by reciprocating sharp blades can be attributed to less availability of carbohydrates for shoot growth, harvesting of immature shoots, and higher severity of harvesting. Wettasinghe *et al.* (1981) also reported that continuous harvesting of shoots at a higher severity reduced average shoot weight. Further, Wijeratne (2003) has shown a reduction in average shoot weight in the harvest as affected by the removal of immature shoots. The picking arms of BatFW did not remove as much maintenance foliage as the reciprocating sharp blades (BatKW and PetKW) (Table 1). Compared to reciprocating blades, the smallest machine with picking arms (BatFW) left a higher number of immature shoots in the plucking table (Figure 3) with minimal damage to the maintenance foliage (Table 1). Thus, manual harvesting and BatFW gave comparably higher shoot weights than the other two machines.

Shoots acceptable for manufacture and damaged shoots

After sorting out the coarse and damaged leaves in the harvest, all the tender shoots are acceptable (good) for manufacture. Damaged shoots (sub-standard), in contrast, result in low quality of the made tea. The percentage (by weight) of good leaves varied significantly ($P<0.05$) among the harvesting methods (Figure 2). The highest good leaf yield was recorded under manual harvesting, followed by BatKW, PetKW and BatFW. The reduction in the % of good leaf (by weight) in the harvested crop in comparison with manual harvesting was as high as 35% for BatFW, while it was 20% and 13% for PetKW and BatKW, respectively (Figure 2).

The highest ($P<0.05$) damaged shoot % in the harvest was observed with BatFW (Figure 2). Horizontally reciprocating sharp blades (BatKW and PetKW), however, caused comparable and less damage to shoots when compared with BatFW, while manual harvesting recorded the least. Figure 2 shows the negative relationship between the fractions of acceptable shoots (good) and damaged shoots in the harvested crop. Vertically rotating picking arms (BatFW) resulted in eight-fold higher damage to shoots than manual harvesting, while horizontally reciprocating sharp blades (BatKW and PetKW) caused only four-fold more damage than manual harvesting (Figure 2).

Despite some of the favourable features discussed above, BatFW caused the highest shoot damage in the harvest (Figure 2). Its vertically rotating picking arms first direct tea shoots into V-shaped valleys (slots) in the static blunt blade after which, they detach from the tea bush and are pushed towards the collecting sack in the same rotary movement. By these movements, some shoots were crushed between the static blade and rotating arms. In addition, when the harvester moves forward the shoots get stuck in the blade slots (valleys) and are further bruised by the scraping action. Therefore, harvested shoots sustained physical damage by both the cutting and collecting mechanisms, rather than a clear cut obtained by the reciprocating blades of the other two machines. When BatFW moves (passes) faster on the plucking table (for higher output), it damages a higher percentage of shoots in the harvested crop or increases the leftovers. Reciprocating sharp blades (BatKW and PetKW), in contrast, cut shoots in a single stroke. Then the cut shoots are either air-blown (PetKW) or pushed towards the collecting sack by two plastic flaps (BatKW) without further damage. Damaged shoots in the harvested crop reduce the quality of made tea (Wijeratne, 2003; Wijeratne and Watson, 2015). Manual harvesting ensured the least damage (less than 5%) to the harvested shoots.

The lowest % of acceptable shoots (good) in the harvested crop was recorded by BatFW (Figure 2) due to a higher % of damaged shoots. Furthermore, its harvest consisted of a very high proportion of immature shoots, while it left a very high (approx. 80%) proportion of dormant shoots in the plucking table (Figure 3). In addition, it also left a considerable number of pluckable shoots in the plucking table (Table 3). Therefore, out of the cutting and collecting mechanisms tested, reciprocating sharp blades (BatKW and PetKW) were found to be superior to the vertically rotating picking arms (BatFW) for ensuring better quality of the harvest.

Shoot composition in the plucking table

Total shoot density, percentage removal of pluckable shoots and damaged shoots left (immature) on the plucking

The total shoot density before harvesting, % removal of pluckable shoots and % damaged shoots left on the plucking table are presented in Table 3. Comparable total shoot densities were recorded under manual harvesting and BatFW (Table 3) while both Kawasaki harvesters with reciprocating blades (BatKW and PetKW) resulted in significantly higher shoot densities than other harvesting methods.

Reciprocating sharp blades removed shoots and maintenance foliage indiscriminately and hence, a majority of the apical parts were removed frequently, irrespective of the blade length. This frequent removal of apical parts leads to the development and emergence of a large number of new tender shoots at a given time (Wettasinghe *et al.,* 1981). Hence, a higher number of small shoots (buds) were found in the plucking tables. In contrast, vertically rotating picking arms (BatFW) generally did not cut all the shoots similar to reciprocating blades, and therefore, led to the development of a lesser number of growing shoots. This makes the shoot density of tea bushes under BatFW harvesting lower than those under BatKW and PetKW, while being similar to manual harvesting.

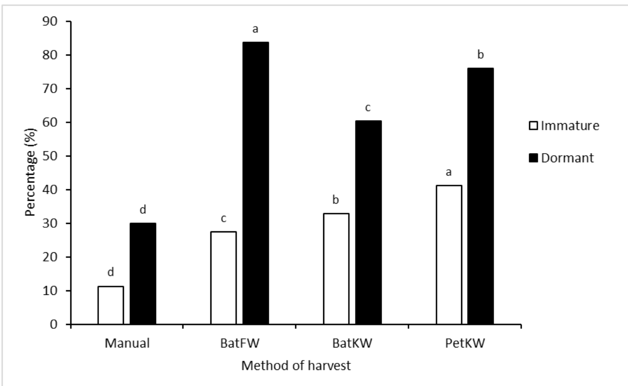
Individual shoot-picking by manual harvesting recorded the highest ($P<0.05$) removal of pluckable (2L, 3L and dormant) shoots from the plucking table (Table 3). Reciprocating sharp blades of BatKW and PetKW recorded less removal of pluckable shoots than manual harvesting. BatFW picked 69% of the total pluckable shoots, which was the lowest among the three machine harvesters. Since manual harvesting picks shoots individually and selectively, it reported the highest percentage of removal of pluckable shoots. Vertically rotating picking arms (BatFW) restricted harvesting to a single cutting slot at a time so that the other five slots remain idle at a given moment. Therefore, tea shoots already reached in such idle cutting slots can remain unpicked and get damaged (scraped) when the harvester moves forward, in addition to damaging immature shoots. In contrast, reciprocating sharp blades of BatKW and PetKW cut everything. Accordingly, around 30% of the pluckable shoots were left unpicked in the present experiment. Both Kawasaki machines (BatKW and PetKW) removed a comparable and smaller percentage of pluckable shoots compared to manual harvesting (Table 3). Pluckable shoots left on the plucking table often overgrow and bring in more coarse material into the harvest, resulting in a low outturn and poor quality of made tea. Leaving pluckable shoots for extended periods delays shoot regeneration and hence, reduces shoot density and yield as well (Wijeratne 2003 and 2012).

The percentage of damaged shoots left (immature/*arimbu*) on the plucking table varied significantly (P<0.05) among the harvesting methods (Table 3). The highest damage was by the reciprocating sharp blades of PetKW, which caused approximately 13 times higher injuries to immature shoots than manual harvesting. Although the shoot damage on the plucking table by BatKW was less than PetKW, it too recorded an 11-fold damage compared to manual harvesting. Of the tested machines, the vertically rotating picking arms of BatFW caused the least damage to the immature shoots left on the plucking table. However, its damage was still eight times higher than that of manual harvesting. Damage caused by manual harvesting to the shoots left on the plucking table (immature/*arimbu*) was negligible (2%) (Table 3). Although BatFW reported very high damage (37%) to the harvested crop (Figure 2), its damage to the shoots left (immature/*arimbu*) on the plucking table was observed to be as low as 15% (Table 3). Horizontally reciprocating blades of BatKW and PetKW, however, resulted in higher damage. Damage to the shoots (immature/*arimbu*) left on the plucking table affects the growth of shoots and results in yield reduction (Wijeratne, 2003 & 2012). Further, in support of these findings, Shankar *et al*. (2016) and Nandagopalan, *et al*. (2014) have also reported considerable damage to the tea shoots with mechanical harvesting.

Table 3: Variation in the total shoot density before harvesting, percentage pluckable shoots removed and percentage damaged shoots left after harvesting on the plucking table [1]

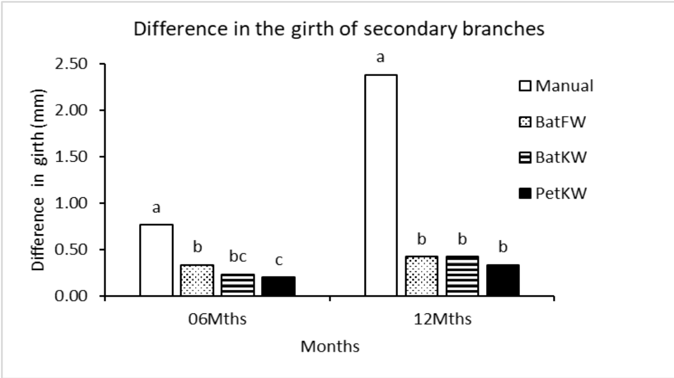
Treatment	Total shoot density (count bush^{-1})	% Removal of pluckable shoots	% Damaged shoots
Manual harvesting	202.02^{b} ±5.96	88.55^{a} ±2.10	1.98^{d} ±0.43
Battery-operated F&W Harvester (BatFW)	194.87^{b} ±7.22	69.15^{c} ±3.91	15.01^{c} ±1.10
Battery-operated Kawasaki Harvester (BatKW)	221.00^{a} ±8.72	73.50^{b} ±3.94	20.97^{b} ±2.00
Petrol-driven Kawasaki Harvester (PetKW)	224.75^{a} ±6.80	71.79^{b} ±4.25	24.97^{a} ±2.81

[1]Means with the same letter(s) in a same column are not significantly different at p=0.05. Each mean is derived from four replicate plots.



Bars sharing the same letter(s) in each shoot category are not significantly different at P=0.05. Immature = immature (*arimbu*) shoots picked and Dormant = Dormant (*banji*) shoots left.

Figure 3: Variation in the percentage removal of immature (*arimbu*) shoots and percentage dormant (*banji*) shoots left in the plucking table as affected by harvesting method.



Bars sharing the same letter(s) in each time duration are not significantly different at P=0.05.

Figure 4: Variation in girthing (measured as diameter) of the secondary branches under different methods of harvesting.

Immature (arimbu) shoots picked and dormant (banji) shoots left on the plucking table while harvesting

The percentage removal of immature shoots showed significant (P<0.05) variation among the harvesting methods (Figure 3). A higher number of immature shoots was removed by reciprocating blades of PetKW followed by BatKW. Vertically rotating picking arms of the BatFW harvester removed a lower number of immature shoots compared to the other two machines, while manual harvesting recorded the least. Further, smaller machines (BatFW and BatKW) removed immature shoots approximately 2-3 times as much as manual harvesting while it was four-fold with the large machine (PetKW). Non-selective mechanical harvesting removes immature shoots indiscriminately (Wijeratne, 2012; Madamombe *et al.*, 2013) and reported a higher removal of immature shoots compared to manual harvesting (Figure 3). Removal of immature shoots (sink) contributes to less photo-assimilation through sink-source imbalance and subsequently, results in poor frame development (Figure 4) and depletion of root starch reserves (Figure 5) and thereby developing less healthy tea bushes with low yields (Table 1) (Wettasinghe *et al.*, 1981; De Costa, 2004; Wijeratne, 2012; Madamombe *et al.*, 2013).

Significant (P<0.05) variations were observed in the percentage of dormant shoots left on the plucking table among different harvesting methods (Figure 3). Vertically rotating picking arms (BatFW) left a significantly higher percentage of dormant shoots on the plucking table followed by PetKW, BatKW and manual harvesting. Compared with manual harvesting, three times as many dormant shoots were left with BatFW and PetKW, while PetKW left only two-fold. Dormant shoots should be removed to break the dormancy and induce new growth leading to higher shoot density. The highest amount of dormant shoots on the plucking table was left by BatFW. Further, its picking arms gave a lighter harvest than the reciprocating blades of BatKW and PetKW. In addition, dormant shoots have short internodes and remain hidden in the plucking table unnoticed. Therefore, they are easily skipped from the picking arms than reciprocating blades. Manual harvesting left the least number of dormant shoots (almost 70% removed). Wider reciprocating blades (PetKW) left more dormant shoots than narrower (BatKW) (Figure 3). Smaller (narrow) machines need several passes on a tea bush to cover the entire plucking surface. Therefore, narrow blades result in varying cutting depths (severities) on the same plucking table and remove more dormant shoots compared to wider blades.

Gain in girth of the secondary branches

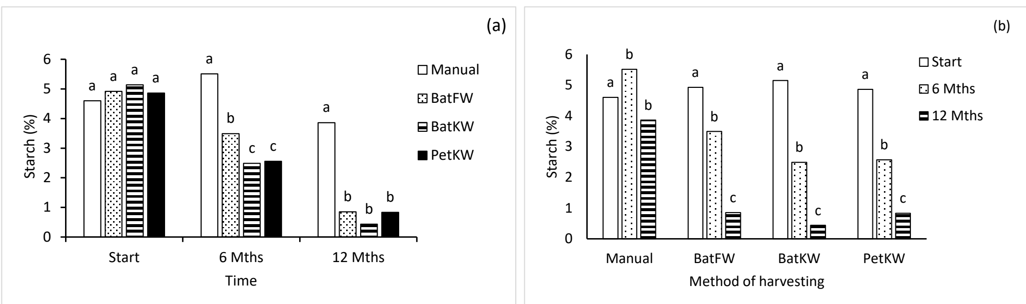
Girthing of secondary branches is an indicator of frame and vascular system development, measured as the difference in the branch diameter before and after the application of treatments (Figure 4). There was a significant (P<0.05) increase in the girth of secondary branches harvested manually compared to mechanical harvesting 6- and 12-months after the commencement of treatment application. Frame development was poor in all the machine harvested bushes even after a short period of six months. However, smaller machines (*i.e.,* BatKW and BatFW) resulted in smaller negative effects than the larger machine (*i.e.,* PetKW) after six months. In the long run (12 months), all machines contributed equally to the reduction of branch girthing (Figure 4).

The cutting mechanism of BatFW was less severe and removed less maintenance foliage as coarse leaves in the harvest (Table 1). This accumulated more maintenance foliage in the tea canopy compared to the other machines and consequently produced a higher amount of carbohydrates (photosynthesis) for growth and maintenance. Therefore, BatFW supported the development of the tea bush frame during the first six months compared to other harvesters, thus supporting an efficient translocation of carbohydrates between the leaf canopy and the root system. However, the girthing of the secondary branches of tea bushes harvested by BatFW was approximately half that of manually harvested bushes. Reciprocating sharp blades of BatKW and PetKW, in contrast, removed more maintenance foliage (Table 1) leading to 3-4 times less contribution to frame development impairing translocation. Long term applications (*e.g.,* one year) of motorized harvesters have reported negative impacts on frame development compared to manual harvesting (Wijeratne, 2012).

Root starch reserves

Root starch levels measured at the beginning, after 6-months, and 12-months of the experiment are shown in Figure 5. Mechanical harvesting significantly ($P<0.05$) reduced the root starch content compared to manual harvesting (Figure 5.a) after 6-months, while BatFW was the highest amongst the machines. After one-year, all motorized harvesters considerably reduced root starch content in equal magnitude to manual harvesting. Further, machines reduced root starch reserves continuously, while manual harvesting increased root starch (approx. 20%) significantly ($P<0.05$) after 6-months (Figure 5.b). However, after one year, all the treatments significantly ($P<0.05$) depleted root starch reserves compared to that at the beginning. (Figure 5.b).

The highest depletion in root starch reserves was (after 6-months) by the reciprocating sharp blades (*i.e.,* BatKW and PetKW), regardless of the blade length. They also affected the production of carbohydrates by removing a higher amount of maintenance leaves (Table 1). Less availability of carbohydrates weakened the growth and hence, branch girthing (translocation) (Figure 4) and thereby, depleted root starch reserves. In contrast, the BatFW removed less maintenance foliage (Table 1) affecting the root starch less after 6-months. However, long term (12 month) application of mechanical harvesters significantly ($P<0.05$) depleted root starch reserves compared to manual harvesting.



Bars sharing same letter(s) in each section of the horizontal axes are not significantly different at P=0.05.

Figure 5: Variation in the root starch reserves as affected by (a) different harvesting methods and (b) different time intervals.

Time taken for harvesting and fuel consumption

The use of labour in each harvesting method is shown in Table 4. Significantly ($P<0.05$) higher and comparable labour requirements were reported by manual harvesting and the BatFW harvester, followed by BatKW and PetKW (Table 4). The PetKW needed 2 men for its operation and used about 5 (4.21) labourers per hectare (LPH) which was comparable with that of BatKW operated by a single person. As explained earlier, BatFW left some pluckable shoots unpicked in its first pass, requiring a second pass. The time taken for the second pass alone contributed 1.16 to the LPH of 5.93 (Table 4).

The tea extent covered was 0.13, 0.17, 0.25 and 0.47 ha/day for manual harvesting, BatFW, BatKW and PetKW, respectively. As PetKW used 2 men for its operation, the requirement of (mechanical) units for plucking operations would be 8, 6, 4 and 2 (units ha^{-1} day^{-1}) in the same respective order.

The average daily (6.5 working hours) output of a manual plucker generally varies from 25-35 kg of green leaf. In comparison, the output of BatFW with a 20 cm cutting width was 60-70 kg per day. The 30 cm long blades of BatKW could harvest up to 100-120 kg of fresh leaf per day while the PetKW (with 60 cm blades) harvested 250-300 kg. The extent harvested by a motorized machine largely depends on the length of the blade (cutting width) (Wijeratne, 2012). The output (kg per day) of a motorized tea harvester is a function of the speed of forward movement and the width of the cutting section, for a given cutting mechanism (reciprocating, rotating, *etc.*). The speed of forward movement is suggested to be a constant since the operator walks along the contour of tea rows without depending much on the slope of the land unless it is very steep. Interestingly, both harvesters with reciprocating sharp blades (*i.e.*, BatKW and PetKW) shared a similar output per unit length of their cutting widths. Thus, the output of reciprocating sharp blades was estimated to be about 4.5 kg $cm^{-1}day^{-1}$ (700 g cm^{-1} hr^{-1}), whereas it was only about 3.5 kg $cm^{-1}day^{-1}$ (500 g cm^{-1} hr^{-1}) for helically arranged, vertically rotating picking arms (BatFW). Therefore, the output of horizontally reciprocating sharp blades was found to be more efficient in the harvesting of tea shoots than vertically rotating picking arms.

Minimizing the impacts of motorized harvesting on growth and tea yield

To mitigate the physiological stress exerted by mechanical harvesting on the tea bush, several suggestions can be made. Due to the non-selective nature of the motorized harvesting machines, the removal of immature shoots could not be avoided without having an engineering solution for developing selective harvesting devices. However, both the higher severity of harvesting and the removal of maintenance foliage can be minimized by careful handling of the currently available plucking machines *i.e.,* primarily by avoiding cutting shoots deep into the plucking table. Further, the operator should be extremely careful not to cut the same area by repeated passes of the machine on the plucking surface. This minimizes the higher severity of harvest and adds coarse leaves and twigs to the harvest. This not only minimizes the removal of maintenance foliage and the addition of coarse leaves but also reduces the damage to *arimbu* shoots left on the plucking table. Application of foliar Zinc and Urea as recommended by the TRISL will cushion the adverse impacts and physiological stress of immature shoot removal, in addition to minimizing the formation and accumulation of dormant shoots. To increase worker productivity by allowing free movement of machines, new tea plantations can be established with hedge-row planting system (2 x 2 x 5 feet) (Anon., 2019). Selecting tea cultivars with shoot and leaf characteristics amenable for mechanical harvesting such as smaller and erect leaves as described by Anon. (2011) also becomes vital to minimize the adverse impacts of motorized mechanical harvesting. The use of mechanical harvesters during heavy cropping seasons (rush crop) and reverting to manual harvesting during lean periods would solve some of the key issues with mechanical harvesting and the present labour shortage for plucking.

Table 4: Labour per Hectare (LPH) required for harvesting operations[1]

Treatment	LPH (Labour ha^{-1} day^{-1})
Manual harvesting	7.74^{a} ±0.45
Battery-operated F&W Harvester (BatFW)	5.93^{ab} ±1.86
Battery-operated Kawasaki Harvester (BatKW)	4.06^{b} ±0.20
Petrol-driven Kawasaki Harvester (PetKW)	4.21^{b} ±0.59
CV%	24.46

[1]Means with the same letter are not significantly different at p=0.05. Each mean is derived from four replicate plots.

It is always better to use fuel operated machines in large estates for uninterrupted harvesting operations as batteries need frequent recharging and their run time decreases with time. Small battery-operated machines, however, would be useful for smallholdings depending on their extent and frequency of use.

CONCLUSIONS

Reduction in the tea yield with continuous use of non-selective harvesters is caused by their adverse effects on yield determining physiological parameters. This reduces tea yield by about 50% compared to selective manual harvesting, irrespective of the cutting and collecting mechanisms of the harvesting machine. Apart from quantitative losses, non-selective motorized harvesting could cause quality losses in the tea yield if not properly adopted.

Non-selective motorized harvesting adversely impacts yield determining physiology of the tea bush by decreasing shoot density, accumulating dormant (*banji*) shoots, causing damage to immature (*arimbu*) shoots left on the plucking table, weakening frame development, removing immature (*arimbu*) shoots (sink) and cutting off photosynthesizing maintenance foliage (source) and depleting root starch reserves.

Although, static blunt blades with vertically rotating picking arms (*e.g.,* BatFW) are less severe in harvesting than horizontally reciprocating sharp blades (*e.g.,* BatKW & PetKW), the rotating action of the picking arms of the former cause substantial damage to harvested shoots and skips some pluckable shoots influencing the quantity (yield) and quality of the harvest. Vertically rotating picking arms (*e.g.,* BatFW) are less efficient in harvesting shoots (500 g cm^{-1} day^{-1}) than the horizontally reciprocating sharp blades (700 g cm^{-1} day^{-1}).

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the kind cooperation, sponsorship and study leave granted by the Tea Research Institute of Sri Lanka.

REFERENCES

Barman, T.S. and Saikia, J.K. (2005). Retention and allocation of 14C assimilates by maintenance leaves and harvest index of tea (Camellia sinensis L.). Photosynthetica, 43 (2): 283-287.

Bore, J.K., and Ng'etich, W.K. (2000). Mechanical harvesting of tea: 1. Yield and leaf standards. Tea, 21(1). 19-23.

Chandrabose, A.S. (2015). Outgoing labour and its impact on the tea plantation sector in Sri Lanka. In: Proceedings of 5th International Symposium 2015, SEUSL: 412-421.

De Costa, W.A.J.M. (2004). Chapter 8: Sink strength. In: Principles of Crop Physiology. Printing unit, Faculty of Agriculture, University of Peradeniya, Sri Lanka, 509-576.

De Costa, W.A.J.M., Mohotti, A.J. and Wijeratne, M.A. (2007). Ecophysiology of tea. Brazilian Journal of Plant Physiology.,19(4): 299-332.

De Costa, W.A.J.M., Navaratne, D.M.S. and Anandacoomaraswamy, A. (2009). Physiological basis of yield variation of tea (Camellia sinensis) during different years of the pruning cycle in the central highlands of Sri Lanka. Expl. Agric. 45: 429-450.

Goldsmith, R., Kilgour, J., (1999). A model to aid management in the selection of tea harvesting equipment. In: Proceedings of a Regional Workshop on Mechanical Harvesting of Tea, Chipinge, Zimbabwe, 8–9 April: 25–39.

Krishnapillai, S. (1983). Effect of cutting and defoliation on nitrogen uptake by young tea plants (Camellia sinensis l.) Grown in sand culture. Tea Quarterly 52(1). Tea Research Institute of Sri Lanka: 13-20.

Krishnapillai, S., Pallemulla, D. and Navaratne, S. (1992). Studies on tea and drought 1. Some observations on drought effects on physiology of tea. Sri Lanka Journal of Tea Science, 61(2): 59-67.

Madamombe, G. Tesfamariam, E. Taylor, N. (2015). Yield decline in mechanically harvested clonal tea (Camellia sinensis(L) O. Kuntze) as influenced by changes in source/sink and radiationinterception dynamics in the canopy, Scientia Horticulturae, 194: 286–294.

Madamombe, G.M. (2008). Effect of mechanical harvesting on the yield and quality of cultivar and seedling tea (Camellia sinensis) in Zimbabwe: a review of the results, 1988/9 to 2003/4. Tea Research Foundation Central Africa Newsletter, 148: 6-14.

Madamombe, G.M., Taylora, N.J. and Tesfamariam, E. (2013). Yield Decline in vegetatively Propagated Tea (Camellia sinensis (L.) O. Kuntze) under Continuous Mechanical Harvesting. In: Proceedings of 2nd All Africa Horticulture Congress. Eds. K. Hannweg and M. Penter. Acta Horticulturae: 857-861.

Manivel, L. and Hussain, S. (1986). Relative sink capacity of developing tea shoots. Two and a Bud, 33 (1-2): 30-38.

Modder, W.W.D. and Wijeratne, M.A. (2002). Plantation agriculture and mechanization: A review of needs and prospects. Journal of National Institute of Plantation Management, 18(1): 2-9.

Mohamed, M.T.Z., Galahitiyawa, G. and Chandradasa, P.B. (2003) Nett out-turn of made tea to green leaf in low-country. Sri Lanka Journal of Tea Science, (68/1): 48-56.

Mouli, M.R.C, Onsando, J.M. and Corley, R.H.V. (2007). Intensity of harvesting in tea. Experimental Agriculture, 43: 41-50.

Nandagopalan, V. Balamurugan, T. and Prabha, A.L. (2014). Impact of modernization of harvesting in tea plantation to improve the productivity and quality (Camellia spp.). IOSR Journal of Environmental Science, 8(9-III): 55-59.

Nayasulu, S.K. (2006). Mechanical harvesting of tea in Malawi: A research review. trfcaNwes, 146:4-14.

Pathiranage, S.R.W., Wijeratne, M.A. and De Costa, W.A.J.M. (2016). Physiological aspects governing yield variation under manual and mechanical harvesting of clonal tea. In: Proceedings of the sixth symposium on plantation crop research. Plantation agriculture towards national prosperity. V.R.M.Vidanaarachhi, Herath, H.M.I.K., M.K. Meegahakumbura, A.D.N.T. Kumara and M.K.F.Nadeesha (Eds.). Coconut Research Institute, Lunuwila, Sri Lanka. 93-100.

Pathiranage, S.R.W., Wijeratne, M.A. and De Costa, W.A.J.M. (2017). The key factors responsible for yield reduction with mechanically harvested tea. Tea Bulletin 26(1 & 2): 24-28.

Pathiranage, S.R.W., Wijeratne, M.A. and De Costa, W.A.J.M. (2018). Physiological effects of mechanized harvesting and ways to minimize its impacts. In: Proceedings of the 236th Experiments and Extension forum, "Minimize economic losses through refining agricultural practices", 3rd Aug 2018, Tea Research Institute of Sri Lanka: 34-49.

Ravichandran, R. and Prathiban, R. (1997). The impact of mechanization of tea harvesting on the quality of south Indian CTC teas. Food Chemistry 63(1): 61-64.

Samansiri, B.A.D., Rajasinghe, J.C.K. and Mahindapala, K.G.J.P. (2011). Agronomic profile of the corporate tea sector tea plantations in Sri Lanka: A diagnostic study in the corporate sector tea plantations. Tea Research Institute of Sri Lanka, p 99.

Shankar, S., Delcien, A.S.R., Shenoy, C., Soumya, S.C. and Anupama S.H. (2016). Semi-automatic tea leaf harvesting machine. International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE) 5 (4): 1156-1160. Available online http://ijarece.org/wpcontent/uploads/2016/05/IJAREC E-VOL-5-ISSUE-4-1156-1160.pdf Last cited 05-04-2018.

Shyamalie, H.W., Pilapitiya, H.M.C.G., Karunarathna, B.M.N.C. and Wellala, N.N.K. (2016) Worker shortage in tea plantations: How big the "Crisis" is? TRI update, Tea Research Institute of Sri Lanka. 15 (1/2): 6-8.

Tanton, T.W. (1979). Some factors limiting yield of tea (Camellia sinensis). Exp. Agri. 15:187-191.

Tea Research Foundation of Central Africa (2007). Annual Report. 7-8.

Tea Research Institute of Sri Lanka (1998-2003). Annual Reports.

Tea Research Institute of Sri Lanka (1998-2011). Annual Reports.

Tea Research Institute of Sri Lanka (2003). Guidelines on plucking. TRI advisory circular (HP2). 1-5.

Tea Research Institute of Sri Lanka (2005 -2006). Annual Reports.

Tea Research Institute of Sri Lanka (2009-2011). Annual Reports.

Visser, T. (1960). Plucking practices in relation to maintenance foliage. Tea Quarterly 31. Tea Research Institute of Sri Lanka, 1-38.

Watson, M. Bandaranayake, J.I.H. and Wettasinghe, D. T. (1982). The use of plucking machines for harvesting tea. Tea Quarterly, 51:58-66.

Wettasinghe, D. T., Nathaniel, R. K. and Kroon, D. D. (1981). Effect of severity of plucking on the growth and yield of low grown tea. Tea Quarterly, 50 (3). Tea Research Institute of Sri Lanka, 123-130.

Wijeratne, M.A. (1996). Harvesting of tea: Manual or mechanical. In: Proceedings of 193rd Experiments and Extension forum, Tea Research Institute of Sri Lanka, 45-50.

Wijeratne, M.A. (2001). Shoot growth and harvesting of tea. Tea Research Institute of Sri Lanka. 1-45.

Wijeratne, M.A. (2003). Harvesting policies of tea (Camellia sinensis L.) for higher productivity and quality. Tropical Agricultural Research and Extension, 6: 91-97.

Wijeratne, M.A. (2012). Pros & Cons of Mechanical harvesting: A review of experience on the tea harvesters tested by the Tea Research Institute of Sri Lanka. Tea Bulletin, 21(2): 1-9.

Wijeratne, M.A. and Watson, M. (2015) 'Harvesting of tea' in Zoysa, A.K.N. (ed) Hand book on tea, The Tea Research Institute of Sri Lanka: 94-104.

Wijeratne, M.A., Vithana, D.W. and Perera, K.T.C. (1996). Harvesting of tea: Manual or mechanical. In: Proceedings of 193rd Experimental and Extension Forum, 30th August 1996. Tea Research Institute of Sri Lanka, 45-50.

Wijeratne, M.A., Vithana, D.W. and Perera, K.T.C. (2000). Mechanization of field practices in tea lands for higher labour productivity. Journal of National Institute of Plantation Management, 16 (1): 8-16.