



Final report

ME4202

Developing a selective tea plucking method for an existing tea plucking machine

By

Index No.	Name	Marks from (5)
090565P	L.N.S. Wijayasingha	
090449N	C.M. Samarakoon	
090468V	K.P.P. Sanjeeva	

Advisors' names, associations and signature

Prof. M.A.R.V. Fernando	Department of Mechanical Engineering, University of Moratuwa	
Dr. H.K.G. Punchihewa	Department of Mechanical Engineering, University of Moratuwa	
Mr. K.H.J. Mangala	Department of Mechanical Engineering, University of Moratuwa	
Mr. R.K.P.S. Ranaweera	Department of Mechanical Engineering, University of Moratuwa	

**Department of Mechanical Engineering
University of Moratuwa
Sri Lanka**

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DECLARATION

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Index No.	Name	Signature
090565P	L.N.S. Wijayasingha	
090449N	C.M. Samarakoon	
090468V	K.P.P. Sanjeeva	

Date:

The supervisor/s should certify the report with the following declaration.

The above candidates have carried out the research included in this research under my supervision.

Prof. M.A.R.V. Fernando	Department of Mechanical Engineering, University of Moratuwa	
Dr. H.K.G. Punchihewa	Department of Mechanical Engineering, University of Moratuwa	
Mr. K.H.J. Mangala	Department of Mechanical Engineering, University of Moratuwa	
Mr. R.K.P.S. Ranaweera	Department of Mechanical Engineering, University of Moratuwa	

Date:

ABSTRACT

Tea production in Sri Lanka is one of the major sources absorbing foreign exchange to economy of the country. Sri Lanka exports high quality black tea, green tea and white tea. To produce these types of high quality tea, mature tea shoots which are with two leaves and one bud should be plucked in the harvesting stage. One million people are involved, directly and indirectly in the tea industry and a large number of them are working in tea estates for tea harvesting. Nowadays, labour shortage and high labour cost move the management to find alternatives for manual tea harvesting and explore the options for mechanisation.

Investigations were carried out to develop a new technology for selective tea plucking. Several experiments were conducted to identify a basic method for selective tea plucking. Data were collected through these experiments and a statistical analysis was performed. Several mechanisms designed based on these information were tested at tea estates. These methods with the ability of selective tea plucking were studied and developed further through investigations. A model of the final design and detailed drawings were made and a selection mechanism was designed. Furthermore, this selection mechanism can be fixed to an existing tea harvesting machine which is unable to selective tea harvesting.

The new technology developed is very simple and the workers who are not well-educated can use this machine easily. Not only the initial cost for implementing the technology is low, but the expected human contribution is lower than that of present situation.

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C. M. Samarakoon

K. P. P. Sanjeeva

L. N. S. Wijayasingha

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Department of Mechanical Engineering,

University of Moratuwa.

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1. INTRODUCTION

1.1 Structure of the report

First chapter is an introduction of the project, which includes a background, motivation for carrying out the project, aim and objectives, a brief methodology and contribution to knowledge including novel aspects. The second chapter consists of a literature review of relevant fields. This includes information about physiology of tea, how mechanisation affects tea bushes, various characteristics of tea harvesting machines and numerous selection methods to identify the correct tea shoot to harvest. Next chapter presents details about experimentations, prototypes, testing, decision-making and research those conducted while developing the selection mechanism. By reading the fourth chapter, the reader would gather knowledge about the final design of the selection mechanism. Fifth chapter is about testing of final design. Finally the last chapter summarises the whole report. It also includes a section on future works that may be carried out in order to improve the mechanism further.

1.2 Background

One of the major industries in Sri Lanka is tea industry [1]. The country's tea production in 2012 was 328,000 MTs [1]. Owing to the adequate rainfall, plenty of sunlight that the island get throughout the year and other encouraging environmental and botanical conditions, Sri Lanka is in a sound position to become a major tea exporter in the world. Also, Sri Lanka had 17.3% share of world tea exports in 2011 [1]. Most of the tea estates in the country are located towards the middle country and the south [1], where the land is wet and mountainous. Tea is grown as bushes and leaves are being plucked, or harvested through the year. Number of tea varieties is grown in Sri Lanka. They yield different qualities, which give a range of final made tea products. In order to produce high quality tea, shoots where there is an unfurled bud and several soft leaves should be harvested [2]. Furthermore, these leaves must be at the correct maturity level that is imposed by the industry standards.

To obtain the best quality, only the few uppermost foliage on every stem is harvested – the famous ‘two leaves and a bud’ – and the stem itself must be left undamaged. This requires

some cumbersome labour. A skilled tea-harvester can collect up to 20kg (44lb.) of leaves daily [2] [3]. It is worthwhile to state about the present condition of the tea industry. Workers harvest the tea leaves. Subsequently, the harvest is transported to tea factories through intermediate personnel for most of the time. However there are instances where tea harvesters themselves transport the yield. These individuals are being paid by the factory on the basis of the weight of their yield. Average daily wage of a male tea harvester in 2012 was Rs. 548 and that of a female was Rs. 435 [1]. After the harvest is processed in the tea factory, tea products of various qualities are produced.

Human involvement is high in tea harvesting fields since availability of selective tea harvesting machines is low [4]. Fundamental facilities that are provided for the families of the workers are at a very low level [3]. As a result, most of the workers in the field of tea harvesting are hardly educated. Therefore, the workers have poor education and poverty level is high. The tea industries have failed to alleviate the poverty of the workers until now [2]. Consequently, there is a major issue in introducing new technologies for them to use. Initially, a good training has to be given if such new technologies are being introduced [3]. These difficulties increase the labour cost as well as reduce the labour pool. Therefore, the necessity of a new and simple technology with a selective harvesting is considerably high. However, difficult-to-navigate terrains where tea is grown and the complexity of discriminating harvestable tea shoots from the others have been resisting factors for the debut of new technologies in the field.

1.3 Involvement of machines in tea harvesting

The first process of producing high quality tea is to harvest tea shoots at adequate maturity level. To execute this task in a comprehensive manner, tea shoots at correct maturity level should be plucked from tea bushes while maintaining the proper bush health [2]. Bush health is a vital factor to maximise the yield.

Tea harvesting stage bears the largest amount of cost of whole process of producing made-tea [3] [2]. Therefore, proper attention should be given for this stage [4]. Machine involvement in tea plucking field is very low in Sri Lanka even though many hand held shears and motorised machines have been developed [2]. The major problem with the existing shears and machines is non-selective tea plucking and loss of yield [2]. Sri Lanka as a high quality tea producer, such non-selective tea harvesting adversely affects the final made tea [2] [5]. Therefore to harvest the mature shoots from bushes, labourers are

involved in the fields. They harvest tea leaves at the correct maturity level and put them in their bags. The Tea Research Institute, Sri Lanka has developed shear harvesting devices which are not motorised [2]. The devices have improved not only output but also the health of tea bushes. However this shear is not commonly used since its usage is tedious and it does not give a solution to labour shortage and productivity.

Therefore, Sri Lankan tea industry is seeking a new technology or a machine with selective tea harvesting. Considerable amount of research and product development are being carried out on this topic. Usage of evolved technology would be fruitful for a country's economy.

These are the main factors those motivate the development of a comprehensive selective tea harvesting machine for local usage.

1.4 Aim

Various types of tea harvesting machines are available in market. However, they lack proper selectivity. Their utilisation in Sri Lankan tea fields would not only degrade the quality of the final product, but also will reduce the yield of tea bushes. Therefore, a selection method should be developed that have least amount of unsatisfactory effects on above-mentioned factors.

1.5 Objectives

- Study the context of the Sri Lankan tea industry
- Study and identify user requirements for a selective tea harvesting machine
- Obtain knowledge on state of the art of tea harvesting process
- Identify selection criteria for discrimination between harvestable and other tea shoots
- Consider different options for achieving selectivity
- Fabricate prototypes for respective options, test them and conduct research and experimentation
- Check whether each prototype achieves the required level of performance. If not develop/change the design and retest.
- Develop the final mechanism

1.6 Design requirements

The machine should harvest only the harvestable tea shoots while leaving other parts of the tea bush intact. It should harvest dormant tea shoots as much as possible. Harvesting mature leaves and stems degrade the quality of the final product. Likewise, harvesting arimbu reduces the yield of the plantation. To illustrate, arimbus are young shoots that will grow into larger ones in the near future. Therefore, by harvesting these, the yield-to-be gets destroyed. Therefore, harvesting both of these should be avoided. However, according to researchers, the priority should be given to protecting arimbu. If the machine harvest mature leaves and stems, they can be removed from yield fairly easily using manual labour. On the other hand, if arimbus get harvested, it reduces the yield in an irreversible manner.

The ambience of a tea bush is highly humid and corrosive. Therefore, if the machine is going to have electronic components, they have to be made water resistant. This increases cost and complexity. Also, the potential machine operators will be mal-educated workers. Therefore, the machine should be simple and easy to operate. Furthermore, it is desirable that the machine can be repaired easily with least of technical skill and knowledge. Concerning these facts, it is desirable that the selective tea harvesting machine would have a mechanical selecting method.

1.7 Methodology

Firstly, a literature survey was performed to understand about the mechanisation of tea harvesting in a global scale as well as to understand about the growth of tea plants in various clones under various environmental conditions. While understanding characteristics of tea plants, existing tea harvesting machines developed recently were studied. Selective tea plucking is used in Sri Lanka since high quality of made tea should be maintained. The level of utilisation of existing machines in Sri Lankan tea harvesting was understood. Also, impact of mechanisation on tea harvesting was clarified. It was seen that hand plucking is the mostly used method since existing mechanisms barely provide any selection.

Various criteria of tea shoots can be used to discriminate between harvestable tea shoots and arimbus. Colour, stiffness, height, texture and number of unfurled leaves of tea shoots can be used for the purpose. If colour, texture and number of unfurled leaves are the criteria to recognise harvestable shoots, an electronic method can be thought to accomplish

selective tea harvesting. It is difficult to develop a mechanical method based on the criteria such as colour, texture. Nevertheless, user requirements confirm that the machine or method should be with simple preparations and it should endure environmental conditions since the ambience of the tea plucking is often humid and corrosive. Considering these factors, height and stiffness are selected as feasible selection criteria.

After making selection criteria clear, stiffness and height of tea shoots were measured using self-made instruments. Hundreds of tea clones are grown in Sri Lanka. They have different growth rates and stiffness values of shoots. All the measurements are done on the clone type TRI-2026. Four prototypes were developed on the basis of stiffness and height. First three prototypes were based on the stiffness of tea shoots. There were some significant drawbacks of these designs. As a result, selection of harvestable tea shoots did not achieve the expected level of performance. Hence, height was considered as another selection criteria along with the stiffness. The forth prototype was constructed based on both height and stiffness. This was the final method for selective tea plucking, which was tested in the field. This method was observed to perform considerably well. Afterwards, the mechanism was attached to as existing tea harvesting machine. The subsequent tests in fields gave successful results leaving a satisfactorily high number of arimbus in tea bushes.

1.8 Contribution to knowledge

Several novel things which contribute to knowledge in the context of tea harvesting have posed through this project. They are described as follows.

1.8.1 Performance measuring index

In experiments and tests to follow, various designs of selecting mechanisms were tested and experimented with. In order to compare their performance, a standardised measurement of the degree of ‘selectivity’ is needed.

This novel index can be used to compare the performance of different selection methods. Increasing the value of this index imply that the selection method concerned has a better performance compared to other methods.

For further details about the index, refer section 3.4

1.8.2 Novel attachment

The final selection mechanism is attached to an existing machine. The name of the machine is Ochiai AM-110VB450 and it was borrowed from Tea Research Institute, Ratnapura. The attachment can be changed easily so it can be used with other existing machines. If the selectivity of this method can further be improved, the performance of the whole machine increases with respect to selective tea plucking.

2. LITERATURE REVIEW

2.1 Physiology of tea

In Sri Lanka, tea plantations are situated in difficult-to-navigate terrains [2]. [2] states that tea is grown either in contour rows or along the slope. However, [3] notes that the majority of local tea estates adopt the method of contour rows. The distance between two adjacent tea bushes in a single row is 2 feet [4]. Furthermore, the distance between two adjacent rows is kept at 4 feet [4]. “The plucking table of local tea bushes are flat and follows the slope of the land” [2]. A tea bush is approximately 1m tall and the canopy is about 1.6m deep [6].

2.1.1 Tea shoots

Tea shoot is a stem where tea leaves and a bud are grown on the top most point of it [2]. Number of tea leaves of a shoot can be taken as a criterion for harvesting [2]. Tender shoots having 2-3 immature leaves and/or dormant buds should be plucked to produce high quality tea [6]. However, [3] states that “two tenderest leaves and the bud that grow at very top of every stem” should be plucked.

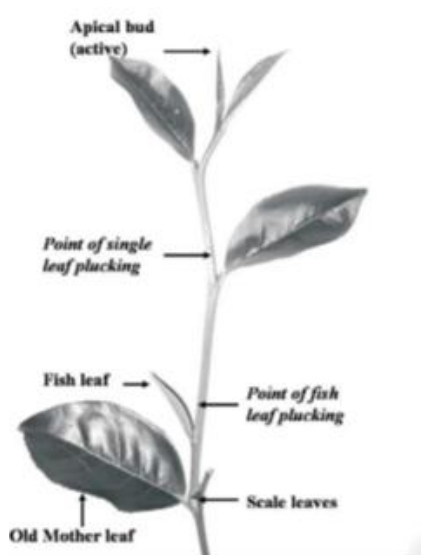


Figure 2 : A typical tea shoot (Source: [2])



Figure 1 : A dormant bud (Source: [2])

In a typical tea bush, there are several generations of tea shoots [2]. In fact, there are 5-6 shoot generations in a typical tea

bush in Sri Lanka [5]. A generation is a family of tea shoots that are at the same level of growth and one generation can usually be uniquely identified by the number of tea leaves [2]. In a single harvesting round, one or two older generations are plucked, leaving the younger ones intact [6]. These younger generations are called ‘arimbu’ [2] [6] [5]. Harvesting ‘arimbu’ results in reduction of productivity of the tea bush [5]. Therefore, it is important for the machine to keep from harvesting those young shoots.

There are over 100 tea cultivars that are planted in Sri Lanka. Shoot growth varies according to the cultivar as well as the region. For example, up country rate of growth is slow due to low temperature. Therefore, specifying a size of harvestable tea shoots is difficult. However, generally, Height of a harvestable tea shoot is generally less than 6 inches [4].

The distribution of tea shoots on the tea bush is an important factor in designing a selective tea plucking machine. The number of tea shoots at the centre of plucking table is greater than that of its periphery [7]. [2] states that there are 140-320 shoots per square metre of plucking table area in low country of Sri Lanka.

The bottom line is, the machine should harvest only one or two elder shoot generations while keeping the younger ones (‘arimbu’) intact. Likewise, it should focus on plucking dormant buds as much as possible. Moreover, the machine should have a way to manoeuvre in terrain conditions described above.

2.2 Impact of mechanisation on tea harvesting

Most of the tea cultivators in the world greatly face a sharp rise in labour cost and labour shortage [8] [9] [10]. Therefore, the conventional method of tea plucking, that is hand-plucking, is replaced by mechanisation [9] [10] [11]. Even though the harvesting process is mechanized, the most suitable method for high quality tea plucking is hand-plucking since the tea can be harvested with minimum injuries to the harvest and the tea bush so that the quality of the harvest is high [8] [12]. However the tea industries all over the world have been seeking to mechanise the tea-plucking process and some countries have already used though the quality of the plucked tea using machines is low. Investigations have to be performed to assess the effects of mechanisation and therefore various researches have been conducted in this area [8] [11] [13].

Based on the research carried out so far, the main effects of mechanization is the change of quality of the harvested tea due to deteriorations of tea quality parameters, the composition of the harvest which is the content of damage shoots, soft dormant shoots, coarse shoots and immature shoots in harvested tea shoots, the reduction of the health of bushes and the yield [9] [10]. Investigations have revealed that harvesting methods affect factors in the tea harvesting field such as pruning cycle, plucking table height, condition of plucking surface too. Two or three leaves and a terminal bud are considered as the best quality tea and it is said as a standard tea plucking [8] [9].

2.2.1 Chemical Composition of tea leaves

Chemical composition of tea leaves is a tea quality parameter, which affects final product and tea processing stages such as fermentation process, withering process [12] [14]. A research has been performed using UPASI-9 (or called chin- ary) clone tea. The column, shear plucked A shows the measurements once inserted machine plucking into the field while shear plucked B represents the chemical composition measured after doing shear plucking several years [8]. The results show that plucking under shearing improves the chemical parameters when the shear plucking is continued several years [8] [Refer Annex A]. The results of the research are as follows:

Table 1: Changes in black tea chemical parameters due to mechanisation of harvesting (source: [8])

Parameters	Hand Plucked	Shear Plucked-A	Shear Plucked-B
Theaflavings (%)	0.78	0.71	0.76
Thearubigins (%)	7.60	8.10	7.90
High polymerized substances (%)	7.10	7.70	7.30
Toatal liquor colour	2.60	2.50	2.60
Water extract (%)	41.90	40.70	41.60
Crude fibre (%)	15.40	14.90	15.20
Caffeine (%)	3.30	3.00	3.10
Protien (%)	3.00	3.30	3.10
Yield (kg/ha/year)	11250	11064	-

Leaf distribution	Good	Poor	Good
Plucking average (kg/worker)	24.00	30.00	-
Cost of production (Rs/kg)	34.30	31.00	-

2.2.2 Yield and bush health

Another parameter affected by shear harvesting and mechanical harvesting is yield, which varies with the plucking method used [Refer Appendix C], round length (also called plucking round) that is the time interval between successive harvests, cultivars grown or tea varieties, pruning cycle, that is time between two successive prunes, and environmental conditions [15] [16]. Cultivars are a plant or group of plant selected for desirable characteristics that can be maintained by propagation. The yield is changed for types of tea plants grown such as clonal teas, seedling tea. Clonal tea such as PC 108, SFS 150, S15/10 refers to the method of controlled breeding of plants to produce the best results while seedling tea such as china seedling tea, Indian seedling tea is breeding naturally and can be propagated by seeds [9] [11] [2]. It needs to be noted that each cultivars or clonal tea is responded differently to shearing and efforts are being made to identify the elite clones that can respond well to shearing [11] [17]. The following diagrams show how to vary the yield with various harvesting methods and variation with the different types of tea such as clone tea and seedling tea.

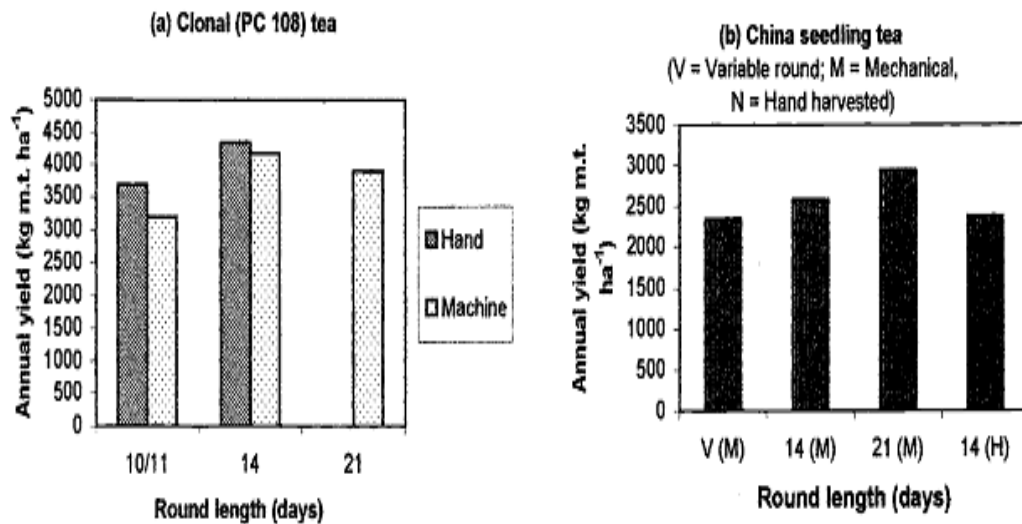


Figure 3: The effect of harvesting method and round length on the yield of (a) clonal (PC 108) and (b) China seedling tea (1999/2000) (source: [9])

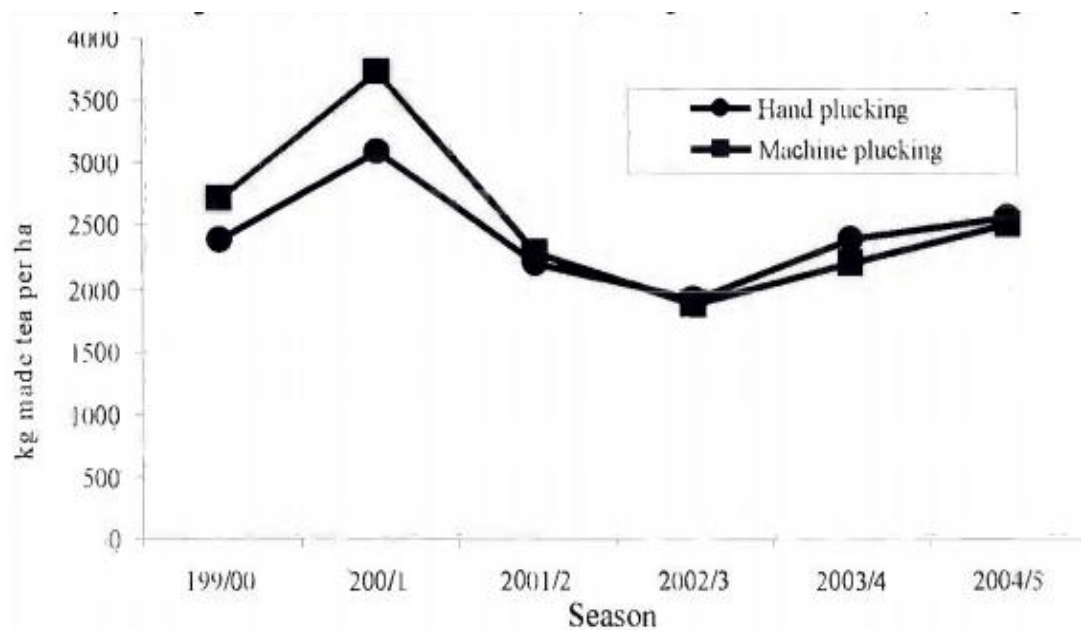


Figure 4: Made tea yield (kg per ha) under hand and machine plucking on china seedling tea (source: [11])

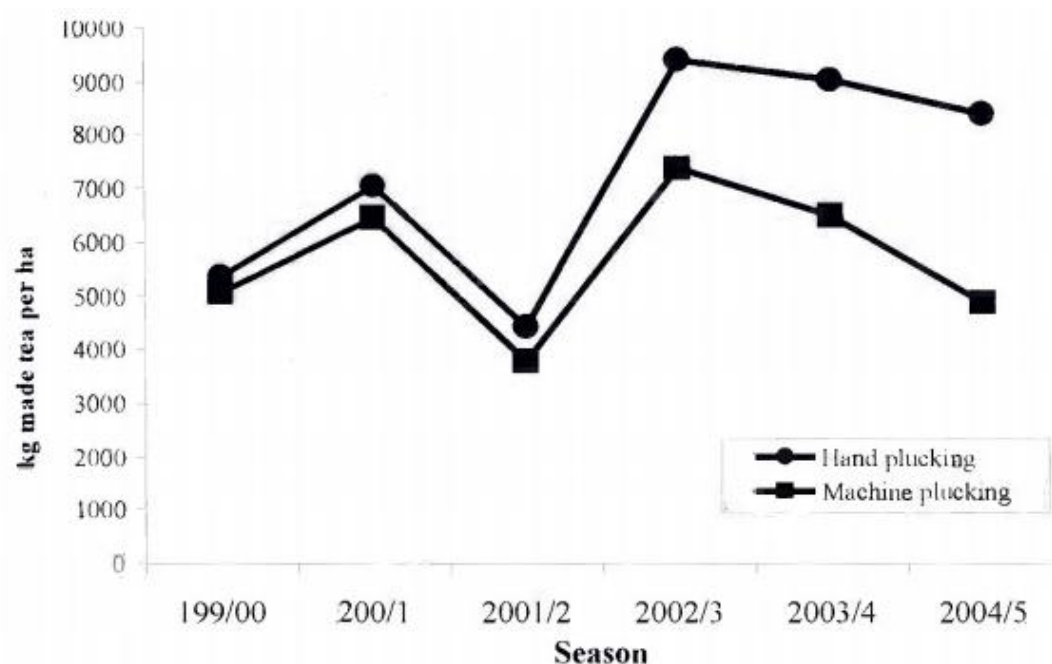


Figure 5: Made tea yield (kg per ha) under hand and machine plucking on clonal PC 108 (source: [11])

According to Fig. 3, when clonal PC 108 and china seedling tea are reaped keeping round length as 14 days and using shear plucking, the yield given by PC 108 is greater than china seedling tea. Several investigations also have shown that under mechanical harvesting, the yield from clonal PC 108 is greater than the seedling tea [9] [16]. Whereas, when the clonal PC 108 are harvested in terms of mechanical harvesting methods for a long period of time (more than about 7 years), the rate of decrease of the yield is greater than that of seedling tea as shown in Fig 4 and Fig.5.

Research has shown that this faster reduction is disclosed that under mechanical harvesting methods, the health of bushes is gradually decreased with time [11] [16]. Therefore a lower yield results after several plucking rounds. However, research has not been performed to disclose that all cultivars or clonal tea are similarly affected the yield as the clonal PC 108 behaves under mechanical plucking [11]. Therefore, research should be conducted in this area to reveal that the other clonal tea or tea varieties behaves in this manner. As a result, new tea varieties can be developed to produce a higher yield with high quality under mechanical plucking. In addition, round length affected the yield in terms of machine plucking [9] [10] [11]. When round length is 14 days, the yield becomes optimal level for PC 108. Therefore, new cultivars or clonal tea may be developed with a better compromise

between mechanical harvesting and the yield such that a higher yield and quality tea can be harvested in optimal round length. Further, it should be proven by performing new research.

2.2.3 Composition of tea shoots

Composition of tea shoots reaped greatly affects the quality of tea harvested and tea processing with increasing the cost of production [2] [Refer Appendix D]. It is difficult to reap higher amount of the standard quality shoots, because of non-selective tea plucking, using mechanical harvesting methods, tea varieties, round length, pruning cycle [9] [10]. Some research has revealed that immature shoots, overgrown shoots and broken shoots were higher under shear plucking than those of hand-plucking [9]. Coarse tea buds and mechanically injured tea leaves have considerably been found in shear cut field or from mechanically harvested tea field [14] [18]. The portion of standard shoots or banjhi shoots was lower under shear plucking than that of hand-plucking [9] [16] [14]. At similar round lengths, the amount of coarse leaves and the number of broken shoots on PC 108 under mechanical plucking have been lower than on seedling tea because of the horizontal leaf pose of this cultivar [16].

When studied Table 2 and Table 3, the composition of shoots harvested depends on round length, tea varieties such as clonal tea and seedling tea, plucking methods [16]. Although the machine plucking method has got worse than that of hand plucking, an exact idea could not be drawn based on these tables and as well as from other research in terms of the composition of shoots harvested [9] [16]. The effect of harvesting method and round length on the components of yield and shoot population per m² of (a) clonal PC 108 and (b) China seedling (1999/2000) are shown in the following tables.

Table 2: Clonal tea PC 108 (source: [9])

Treatment		Immature	Standard	Over	Soft	Broken	Coarse	Good	Pluckable
Plucking	Round	Shoots	Shoots	Grown	banhji	Shoots	Laef	Laef	Shoots
method	Length	(%)	(%)	Shoots	(%)	(%)	(%)	(%)	(m ⁻²)
				(%)					
Hand	10/11	1	38	25	11	25	4	71	81
Hand	14 days	3	26	28	14	25	6	66	66

Machine	10/11	4	31	10	7	33	9	81	60
Machine	14 days	3	30	17	10	29	10	73	78
Machine	21 days	2	26	29	11	23	11	60	85
Mean		3	30	22	11	27	8	70	74

Table 3: China Seedling tea (source: [9])

Treatment		Immature	Standard	Over	Soft	Broken	Coarse	Good	Pluckable
Plucking method	Round length	Shoots (%)	Shoots (%)	Grown Shoots (%)	banhji (%)	Shoots (%)	Laef (%)	Laef (%)	Shoots (m ⁻²)
Hand	14	1	30	28	17	27	7	70	69
Machine	variable	2	28	18	15	23	10	71	58
Machine	14	2	30	27	16	22	9	65	76
Machine	21	1	21	38	17	21	9	53	83
Mean		2	27	28	16	23	9	65	72

2.3 Selection methods

There should be a robust method for a selective tea plucking machine to select only the proper (harvestable) tea shoots. At the same time, it should leave the younger shoots intact.

2.3.1 Achieving selectivity using mechanical methods

2.3.1.1 Selecting grass seeds

Grass-seed harvesters are being developed in the UK, USA and Australia with a moderate degree of selectivity [19]. It is required to harvest only grass seeds, without harvesting parts of stems of other parts in order to produce commercial grass-seeds [20]. Grass seeds are located in grass flowers which grow on top of stems [21] [22].

2.3.2 Firmness and maturity of food as selection criterion

There are various methods to measure maturity of fruits. Their mechanical properties are commonly used to measure maturity [23]. Firmness of a fruits is directly related to its

maturity [24]. Tea shoots that are ready to be harvested and young shoots are at different maturity levels [2]. Hence, there is a noticeable possibility that techniques used to measure fruit maturity could be adopted to form a competent tea shoot selecting mechanism.

2.3.2.1 Destructive methods

One of the conventional methods to measure firmness of fruits that is in wide usage is ‘Magness-Taylor method’ [23] [25] [26] [27] [28]. This is a destructive method. Since it is necessary to measure the maximum force required to penetrate the fruit in order to measure its firmness [23] [27] [28]. This test has proven to be successful for apples [29] and peaches [7] [26]. However, damages to fruits caused by penetration and highly localized measurements (measurements do not represent the properties of the whole fruit) are drawbacks [23] [27]. It can be concluded that if this method is to be used to select tea shoots, a mechanism to penetrate them and to measure the force to do so needs to be utilized.

2.3.2.2 Piezoelectric methods

A range of non-destructive methods to measure maturity of fruits are being developed. Vibration-properties [29] and resonance characteristics [30] could be taken as measurements of maturity of a fruit.

2.3.2.3 Impact methods

According to [23], fruits can be impacted on rigid surfaces to measure their maturity. [29] and [27] has bounced peaches onto a load cell from a certain height and measured their maturity successfully. Likewise, compressing fruits with a rod and measuring the deformation and applied force can yield measurements of firmness and maturity [23]. [27] and [31] suggests a method to measure fruit firmness by blowing a current of air and measuring the deformation of fruits using a laser-based method. In an arrangement made to separate potatoes from clods, both of these were hit by a revolving cylinder. As the restitution coefficient of potatoes was different from that of clods, they were thrown at different distances. Hence, they could be separated [27]. When it comes to selectivity of

tea shoots, each tea shoot can be impacted and the reaction has to be measured and quantified.

2.3.3 Acoustic methods

In these techniques, food items are impacted with a force and their acoustic responses were measured with the intention of estimating certain quality-related characteristics [23]. In a research paper, [23] notes that fruits can be impacted mechanically. Subsequently, their acoustic responses are quantified using a microphone to categorize them according to their firmness [23]. Likewise, acoustic methods have been used to determine moisture content and defects of seeds [32], uncover insects in grain stores [33], detect softening of fruits [23], separate damaged pistachio nuts [30], measure firmness of melons, cherries [30] and apples [34].

Ultrasound-based techniques are also used to determine the quality of fruits, drinks and oils [32] [28]. However according to the opinions of [27], ultrasonic techniques are not suitable for fruit quality measurements.

In the context of selecting proper tea shoots, each of them can be impacted mechanically. After, the acoustic response can be measured. However, if the impacts are imposed using a pure acoustic method, that is using a speaker; several shoots in the range of the speaker will be impacted. Therefore, a technique to uniquely identify acoustic reaction of each shoot should be utilized.

2.3.4 Optical methods

2.3.4.1 Near infrared reflectance

This technique involves transmitting infrared radiation to an object and analysing the radiation that is transmitted back by the object in order to accomplish some degree of detection [27] [29].

This approach is used to determine maturity of mangoes [28], uncover insects hiding in wheat kernels [30], identify chemical composition and species of various seed types [32], firmness and sugar content of sweet cherries and apples, juiciness and softness of woody peaches and kiwi fruit [27]. In addition, a spectrophotometer; a machine that measures infrared readings has been exploited to measure maturity of mangoes [28]. Nevertheless, according to [28], noise level of readings was too high.

However [26] states that results acquired by near infrared reflectance approach are not very promising.

2.3.4.2 Machine-vision systems

In these systems, cameras are used to capture images of the environment [35] [36] [37]. Subsequently, digital image processing (on acquired images) techniques are used to detect objects and separate them from the rest of the surroundings [35] [38]. [37], [38], [35] and [39] have utilized software algorithms to reduce noise of the images and to identify desired targets. However, [36] has implemented physical polarization filters apart from the software filters in order to filter-out noise.

Machine vision systems are used by researchers to implement recognition and navigation path extraction systems for pineapple orchards [38], apple [37] and strawberry [36] harvesting robots, olive fruit recognition systems [35] and leaf-type-identifying systems [39].

2.3.4.3 Other optical methods

Laser-based instruments are commercialized for on-line usage to detect maturity and damages of pears, apples, peaches and Sharon fruit [40]. This system achieved a rate of 2-5 fruits per second depending on the type and condition of fruits [40]. [28] describes an arrangement that uses colourimeters (devices that quantify colour) to measure fruit-qualities. However, they tend to be unreliable since only local observations are made [28]. Apart from these methods, machine-vision systems can be used for object identification [28].

2.4 Power consumption

Power consumption and economy of the machine have strong relationship in the machine. Therefore, selection of an appropriate power source for the machine is needed. First we must consider factors which are affected for total power consumption of the tea plucking machine.

2.4.1 Factors to decide power consumption of the machine

2.4.1.1 Cutting methods of the tea leaf

They are hand plucking, shearing, impact and mechanically operated blades are numerous methods which can applicable for separate the tea leaf from the bush [41]. Energy requirement for above mentioned methods can be fulfilled by either manually form operator or with aid of several energy converters as combustion engines or electrical cells. Different kind of blades and plates are quite useful for shear the tea leaf. Mainly there are three types of blades, namely circular, sickle shape and straight blades [41]. Blade properties of sharpness, material used, rake angle and the rotating speed or reciprocating speed can significantly affect the energy requirement for cutting [6] [8]. Apart from them, plant inclination angle, strength of the stem, fibre content and its moisture content also affect to the cutting energy requirement [42]. Experimental results have carried out under above mentioned facts are shown in the appendix B. Those experimental relationships may be useful for selection of proper blade parameters for shearing.

2.4.1.2 Collecting method of separated tea leaf

Blowers, conveyors and sliders are different mechanisms involves with collection of separated tea leaves. Maintain the expected quality of tea leaves are major consideration than power consumption in has given more priority when select the method. However reduce power consumption due to friction, vibration, heat generation and noise are additional benefits can be involved [6].

2.4.2 Different power sources

Both renewable and non-renewable power sources can be used as the main power source. There are various means, which can fulfil the energy requirement for operate the machine. Renewable wireless power supply provides more benefits in field operations compared with non-renewable power sources [43].

2.5 Characteristics of different existing tea plucking methods

Table 4: Advantages and disadvantages of existing tea plucking methods

Machine	Advantages	Disadvantages
TRI Shear (Stepped Shear)	Selectivity can be achieved	Less productivity (40-

	Hand motion is less compared with long handle scissors	60kg/day) Damage to tea bushes
Hand held shears 	Selectivity can be achieved manually.	Less productivity Difficult to hold the shear when tea leaves get collected to the collection pan
Battery operated machine 	High production rate compared to shears (50 – 100 kg/day). Less noise and vibration compared with harvesters with combustion engines. Low damage to bushes	No selectivity and therefore quality of plucked leafs are reduced. Damage to the tea shoots
Single operator required cutters 	Low damage to tea shoots compared with battery operated machine	No selection at all (Cuts everything belongs to the blade level) Severe damage to the tea bushes
Tractor type machines 	High production rate compared with the above described machines. Can pluck over 1000 kg per day.	Can use only for tea bushes are arranged according to the machine ergonomics and flat areas. Not suitable for hill country areas and there is no selectivity at all.

2.6 Ergonomics

Ergonomics of the machine is important to make a machine which can enhance operator performance, productivity and quality of work. Machine might eliminate or reduce operator discomfort, fatigue, physical stress and prevent accidents or injuries [41]. Main ergonomic factors considered for hand – held machines are handles, static forces and loads, dynamic reaction force and vibration [42] [43]. Following has brief discussion regarding ergonomics of invented tea plucking machines.

Hand held scissor type shears – Hand tools like scissor type shears have mass is around 750 – 1500g and blades and trays are about 20 – 30 cm long [2]. Those tools have proper grip due to long handles. There is a tilted tray on one of blades for collect tea leaves. This makes location of the centre of gravity is unsymmetrical. Due to this fact it generate twisting moment on the operators hand and it increase gradually with number of tea leaves collected. TRI of Sri Lanka has further developed the hand held shear without handles as shown in the Figure 6.



Figure 6 : Hand held TRI shear (source: [4])

This shear has not long and prominent handles. It has mass less than 400g [2]. Two steel blades are fixed about 2.5 cm above the bottom of the leaf collecting tray. One is fixed to the leaf collecting tray and other to the handle [4]. This development helps to reduce the motion of operators hand and improve the selectivity. Collecting tray is held by one hand while moving the blade by other hand of the operator. Centre of gravity is still not exactly symmetric relative to the operator body. However, it does not make more uncomfortable compared with the previous type in operation.

Single man operated motorised machines – Power source (engine or battery) and cutting part are held separately in this type of machines. Engine/battery is mounted on a frame by

which the operator shoulders the harvester on his back. Power transmitted through a flexible rod which has the length around 80 - 100cm [8]. There is possibility to entangle the flexible rod with tea bushes during the operation. The operator holds the cutter in both hands and moves it over surface of tea bush. Additional labour is required for hold the collecting bag as ergonomics principles emphasise. These machines have mass around 6 – 10kg [11].

Two men operated motorised machines – Main difference between this type of machines and single man operated machines are engine is mounted on the one side of the casing of cutting part [44] [45]. Centre of gravity is located closure to the side of engine has mounted. Two workers are required to hold machine by two sides and extra labour is required for hold and replace the collecting bags, as this becomes heavy and become difficult for the works to carry [46].

Major conclusions can make from above machines are most of them does not have symmetric centre of gravity with respect to the operator body as mentioned in the facts above. Hence, it causes to generate extra moments on the operators hand while making uncomfortable during the operation.

2.7 Different cutting methods

2.7.1 Which cutting mechanism to use?

There are various cutting mechanisms and blade shapes involved in the cutting process of existing tea plucking machineries such as rotary blades (circular, sickle shape and finger type), scissor mechanism, reciprocating straight blades. Instead of above used methods gear type cutters, solenoid mechanisms and cam rotators are also applicable in tea shoot cutting process. Since it is considerable cutting mechanism with lowest impact to the tea bush and harvested tea shoots.

2.7.2 Scissor mechanism

Primitive tea plucking equipment's like long hand shears and step shears are used scissor mechanism to shear tea shoots for separate from the bush. These shearing cases to do considerable damage to the tea bush and it leads to reduce the tea harvest in the next plucking cycle [2] [3]. Most of these equipment's are manually controlled and have less production rate. Instead of it there are ergonomic issues and therbligs when operate long

handle shears such as high search time, time requirement to position the equipment, hand motion in large area and centre gravity of the equipment is not symmetric relative to the users body due to collecting pan is located on the one side of the scissor blade which makes user more uncomfortable during the operation.



Figure 7: Long handle shear and Step shear (source: [4])

2.7.3 Rotary blades

Mainly there are three types of rotary cutting mechanisms are used in the existing tea plucking machines as circular shape cutters, sickle shape cutters and finger type rotor cutters. Among the various type of machines cylinder type results the more broken tea leaves compared with the reciprocating mechanism. Main reason is cylinder type blades liable to broke tea leaves due to its speed of motion and cutting speed. When there is low cutting speed and high rotating speed causes to duplicate the cutting of same leaf. Hence, for reduce the damage cutting speed and rotation speed should be optimized.



Figure 8: Rotary cutters (source: [4])

When compare cutters with circular or shear shapes and finger type as shown in the above figure damage to the tea bush is less in finger type cutters. However, it causes to damage 30% of tea shoots after pluck due to rubbing and duplication of cutting effort [3] [5] [51].

2.7.4 Reciprocation of straight blades

This cutting mechanism is applied in the most of the modern tea harvesters. It has ability to achieve high production rate compared with shears and rotary cutters. This mechanism is quite useful due to can perform higher cutting speed and blade motion without duplicating the cutting effort on a single tea shoot. Hence, damage to the tea shoots after separation is considerably low compared to the finger type rotating cutters.



Figure 9: Machines with reciprocating cutters (source: [42])

2.7.5 Gear type cutters

Gear type cutters are also same as rotary cutting mechanism and main difference is there can be used multiple cutting edges which are not performed cutting operation continuously. In this mechanism can use two gear wheels rotate in opposite directions simultaneously and each edge of gear teeth is applicable as cutting edge. Frequency of cutting is depended on the number of teeth's in two gear wheels and rotating speed.

2.7.6 Solenoid mechanisms

These types of mechanisms are quite useful in discontinuous cutting. Cutting edge is moved towards the shoot by means of a pneumatic or electromagnetic actuator based on the control signal provided by the control unit of the machine. This kind of arrangement is really helpful to when deal with electronic system such as image processing, sensing of tea shoots for selection to pluck. When the suitable tea shoot get in to the cutter, actuator release based on the signal provided by control unit.

However, by considering all of above mentioned cutting mechanisms we have selected reciprocating type cutter for our design. There were different advantages and disadvantages

in the above mechanisms and based on the availability and quality of production reciprocating type is the most suitable for implement our selective tea harvester.

2.8 Probable Collection Methods

2.8.1 Conveyers

Conveyors are quite useful to collect separated tea leaves. Some of the existing machineries have used this method to carry separated tea leaves in to the collection bags. There are several kinds of useful conveyors which might be applicable for collection part of the tea plucking machine. Major consideration given here is ability of carry tea leaves without damage. Unless expected quality of tea may not obtain. Mainly there are two types of conveyors as belt type and bucket type. Belt type conveyor with path way in two sides or cover it from side and top is suitable for transport tea leaves from cutter to the collection bag. Bucket type is applicable with or without external coverings.

2.8.2 Blower

Most of the modern existing tea plucking machineries use blower for blow separated tea leaves in to the collection bags. It has less possibility to damage the tea leaves compared with the conveyors because of less possibility stuck the leaf in the pathway to the collection bag and gets damaged. For the blower there may be additional motor is required and it may lead to increase the weight and cost of the machine.

2.8.3 Robot Arms

This method is still not applicable in any sort of existing tea plucking machineries. Grabbing of tea leaves can do with aid of vacuum system at the end of arm which is pointed towards the separated tea leaves or can use some soft grippers for hold the leaves and move in to the collection bag. Robot arm with a vacuum system is quite safe

method compared with two methods above mentioned and high cost involvement, increase complexity of the machine are drawbacks of this method.

3. DESIGN OF THE MACHINE

3.1 Which selection criterion to use?

There are various criteria of tea shoots that can be used to discriminate between harvestable tea shoots and arimbus. According to harvesters and researchers, colour, stiffness, height, texture and number of unfurled leaves of tea shoots can be used for the purpose. Since it is more desirable if the selecting mechanism will be a mechanical one, colour, texture and number of unfurled leaves can be opted out. This leaves the designer with two options, namely height and stiffness.

Note: all statistical analyses were performed using the software ‘Minitab’.

3.1.1 Height of tea shoots as selection criteria

Heights of tea shoots at a tea estate where the clone is TRI2026 were measured. Furthermore, the tea estate was located at Attanagalle.

Arimbus and harvestables were taken as two populations. By observing the results of statistical analyses, it was seen that the heights of the two populations poses significant difference of their heights, with a p value of 0.00. Please refer appendix for further detail. Therefore, height can be used as a selection criterion.

3.1.2 Stiffness of tea shoots as the selecting criteria

The force required to deflect tea shoots were measured. The clone of tea is TRI2026. Further details of this experiment are included in up-coming discussions. The data collected are included in the appendix.

As before, a statistical analysis was performed to check whether arimbus and harvestables have significantly different stiffness values. Results showed that they were significantly different with a p value of 0.00. Please refer appendix for further details. Therefore, stiffness too can be used as a selection criterion.

3.2 Finding stiffness values of tea shoots

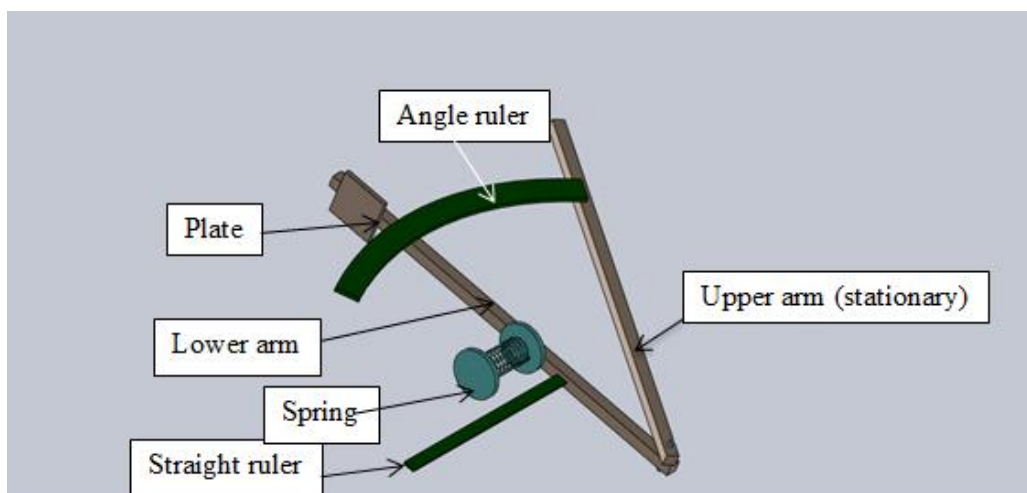


Figure 10 - Stiffness tester

In order to verify whether arimbu and harvestable tea shoots possess considerably distinctive stiffness values, measurements of various tea shoots should be taken. For doing so, an instrument was devised.

This piece of equipment is taken near the tea shoot which the stiffness should be measured. Then the angle between the lower and upper arms are made zero. Subsequently, the centre of the 'plate' is touched with the shoot. Afterwards, the lower arm is pulled against the shoot, along with the plate by pulling the spring. Then the amount of the deformation of the spring is measured by straight ruler readings. Furthermore, initial error of the deflection of spring (due to friction between arms) was 3mm. This is done for several angles of deflection. This angle is measured using the angle ruler and it measures the angle between two arms.



Figure 11 - Equipment to measure stiffness of tea shoots

Using this equipment, forces that are required to deflect tea shoots were measured and recorded. Afterwards, a linear multiple regression analysis was performed on data. This resulted in two equations those explain forces required to deflect both arimbus and harvestables.

F_h and F_a are the forces required to deflect harvestables and arimbus. x is the deflection while h is the height to the point being investigated from the plucking table. Both are measured in mm.

$$F_h = 4.74 + 0.117x - 0.0257h$$

This equation is valid for $50 < h < 185$ and $13.55 < x < 40.65$

$$F_a = -0.749 + 0.0282h + 0.103x$$

This equation is valid for $40 < h < 70$ and $13.55 < x < 40.65$

Next task is to find a method to do the selection at this force.

3.2.1 Finding the spring coefficient of the spring

Various weights were hanged at an end of the spring and its deflection was measured using a straight ruler. Data are included in the appendix. By analysis of data, spring constant was found to be 2.07 g/mm.

Stiffness-measuring equipment uses a straight mm ruler to measure deflection. Spring coefficient is 2.07 g/mm. Therefore, minimum measurement of the stiffness-measuring is 2.07 g.

3.3 Finding an appropriate method for selection

With some intuition, it was thought that the deflection of a flexible stripe can be used to select tea shoots. The characteristic that will be used to discriminate between arimbus and harvestables is the amount of deflection that the stripe undergoes. The plastic stripes are to be extracted from 'Elephanthouse' ice cream containers (Yellow colour).

The stiffness values of such plastic stripes of varying lengths were measured using custom-made equipment (refer Figure 12 - **Equipment to measure stiffness**12).

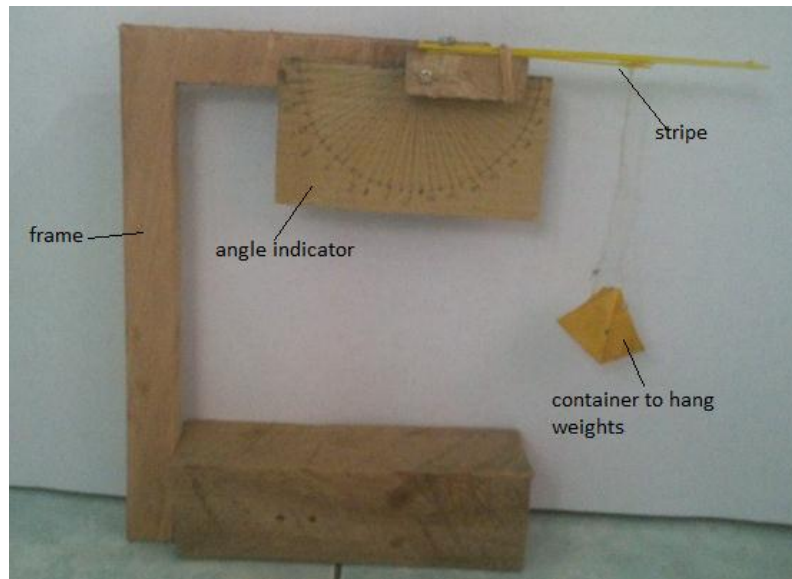


Figure 12 - Equipment to measure stiffness

Please refer appendix for further details. By this analysis, it could be concluded that the plastic stripe can be used for the task.

3.4 Measuring selectivity

In experiments and tests to follow, various designs of selecting mechanisms were tested and experimented with. In order to compare their performance, a standardised measurement of the degree of 'selectivity' is needed.

When doing experimentation with the design prototypes, a certain region on a tea bush is selected. The number of arimbus and harvestables are counted. Then the selection method in interest is performed on the selected area. Subsequently, the resulting number of harvestables and arimbus are counted.

Define selectivity, $s = \frac{10^{h/H}}{10^{a/A}} * 10$

Where,

H - Number of harvestables in the area before selection

h – Number of harvestables that were selected to be harvested

A – Number of arimbus before selection

a – Number of arimbus that are selected (erroneously) to be harvested

When the selection mechanism becomes better, s increases. This factor ranges from 1 (worst case) to 100 (best case). Here, worst case is all arimbus and no harvestables get harvested. Best case is vice-versa.

3.5 Prototype 1

From the above examinations, it is apparent that the stripe can be used to select tea shoots. However, practical verification is always desirable. Therefore, equipment was fabricated where the length of the stripe can be changed. The angle of the stripe to the direction of traversal can be adjusted too.

This is the initial prototype that was fabricated (refer Figure 13). In the front, there is a plastic stripe mounted on a rotatable block. A straight ruler is mounted on another block that can be moved along a slot. This adjustment can be used to change the deflection amount of the plastic stripe.

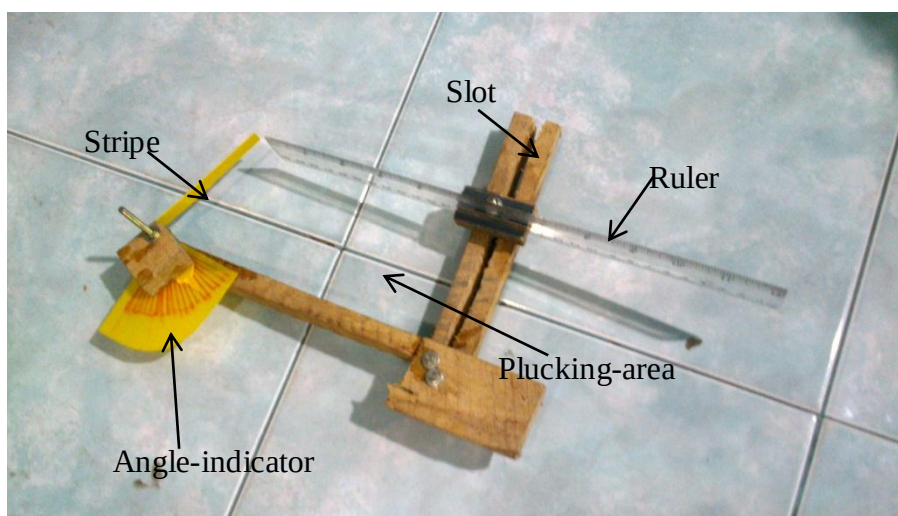


Figure 13 - Prototype 1

The piece of equipment is moved on the tea bush approximated 10mm above the plucking bed. The direction of movement is parallel to the ruler. When an arimbu gets contact with the stripe, it is supposed to slide along it till it goes beyond the ruler. When a harvestable shoot comes, it is supposed to bend the stripe and go inside the plucking-area.

3.6 Design of the plastic stripe

3.6.1 Avoid tea shoots from bending

When tea shoots contact the initial part of the plastic strip, all of them should bend in the side ways. They should not bend in the direction parallel to the advance of the machine, as this will cause them to bend beneath the plastic strip and get inside it. This may not only damage the tea shoots, but also will result in arimbus to end up in the region where there should only be harvestable tea shoots. In turn, this will degrade the selectivity of the machine. Therefore, it should be avoided.

A mathematical analysis was performed to find the optimum angle of the stripe to the horizontal where tea shoots will show a minimum deflection, perpendicular to the stripe. This resulted in an angle of 70^0 . To see how this value was obtained, refer section 5.6.2 in appendix.

3.6.2 Maximising the deflection

The proposed tea shoot selecting method employs a fully mechanical method. To illustrate, it monitors the deflection of a plastic stripe when get in contact with tea shoots. After monitoring, it decides whether to cut the tea shoot or not. The sensitivity of the system will increase with increasing amount of deflection of the plastic stripe. Therefore, the goal is to find the length of the stripe so that its deflection at its free end is maximised.

A mathematical analysis was performed to find the length which resulted in a length of 70mm. Refer appendix for derivation of this value.

3.6.3 Summary of design of the stripe

Length = 70 mm

Inclination to the direction of advance of the machine = 160^0

Furthermore, this stripe will deflect 23 mm when in contact with a critical tea shoot. Most of the arimbu will result in a lesser deflection while most of the harvestable ones will cause a greater one.

3.7 Finding the coefficient of friction between tea shoots and plastic

For the derivations in section 3.6, the value of coefficient of friction between tea shoots and the plastic material is needed. Therefore, an experiment to find the value if performed.

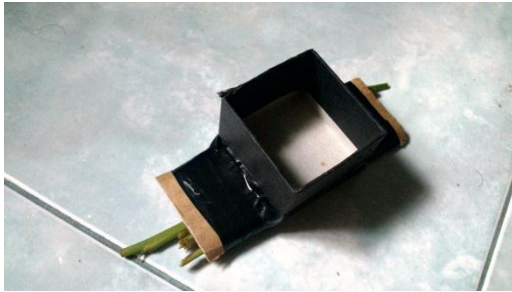


Figure 14 - The container



Figure 15 - tea shoots attached to the container



Figure 16 - The container on the plastic plane

Harvestable tea shoots were attached to the underneath of a container as shown in Figure 15. Then this equipment was kept on an inclined plastic plate (refer Figure 16). Afterwards, weights were placed inside the container and the plane was inclined till the container, along with the weight just begins to slip along the plane.

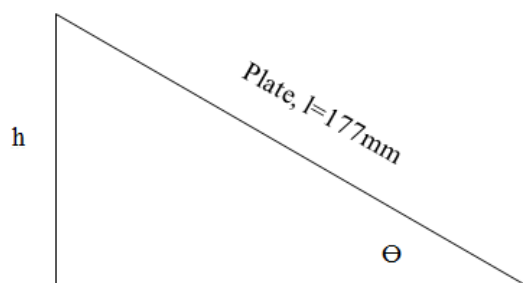


Figure 17 - Schematic of the equipment

The length of the plate is 177mm. according to the figure 17, h was measured as the weight is changed. The coefficient of friction, μ can be found as $\mu = \tan\Theta$. The data obtained are included in the appendix.

The mean coefficient of friction is obtained by averaging $\tan\Theta$ values obtained from each observation. Therefore, the coefficient of friction is 0.54.

3.8 Testing of prototype 1

After several trial-and-error tests, it was found that if the distance between the front edge of the ruler and the free end of the stripe is kept at 10mm, the results would be moderately acceptable. Therefore, it was kept at that value throughout the test. The test was carried out for several lengths of the stripe. Also, the angle of the stripe to the direction of advance was changed for each length.

Length was varied from 30mm to 80mm while the angle ranged from 0^0 to 70^0 . Each angle-length pair is tested for 10 harvestables and 10 arimbus. Suppose that out of the tested harvestables, 'h' number successfully arrived into the plucking-area. In the subsequent testing of arimbu, 'a' number erroneously entered into the latter area. Furthermore, assume the total number of harvestables tested is H and that of arimbus is A

L= length of the stripe

Θ =angle of the stripe to the direction that is perpendicular to the direction of advance

Table 5 - Selectivity of various angles and lengths of the stripe

L	Θ	h	a	s
30	0	9	10	0.91
30	10	3	8	0.44
30	40	5	10	0.55
30	70	7	6	1.14
40	0	8	7	1.13
40	30	6	7	0.88
40	60	8	6	1.29
50	0	6	5	1.17
50	30	6	5	1.17
50	60	7	5	1.33
60	0	6	4	1.40
60	30	9	6	1.43
60	60	9	4	2.00
80	0	6	5	1.17

80	30	7	8	0.89
80	60	8	7	1.13

When looking at table 1, it can be seen that maximum selectivity occurs around length of 60 mm. Furthermore, s increases as the angle increases. From this data, it can be inferred that maximum selectivity would occur at an angle around 60^0 .

3.9 Prototype 2

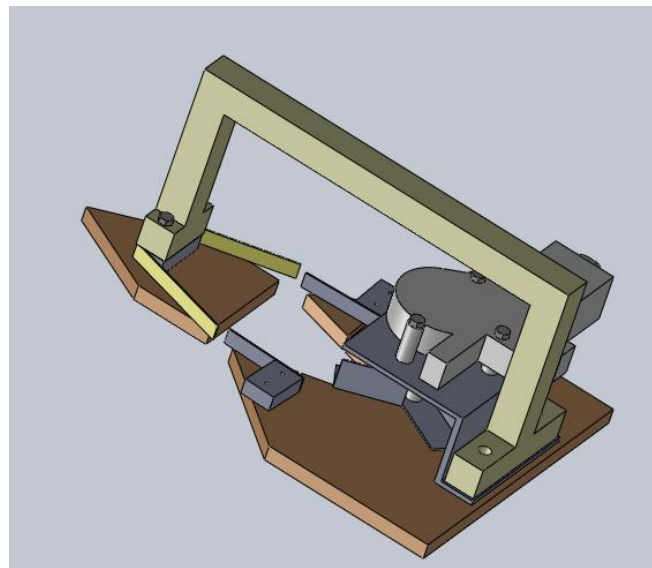


Figure 18 - Prototype 2

This operates similar to prototype 1. However, there are two plastic stripes. Therefore, two selecting guides are needed. Harvestable shoots are supposed to come to the cutting zone after deflecting the stripes. The rotating blade is used to cut the shoots. This blade is being rotated continuously.

This prototype without the cutting mechanism was tested in a tea estate.

3.9.1 Testing of prototype 2

For testing, an area on the tea bush where there are several harvestables and arimbus is selected (subjects). The machine was traversed across this area. Afterwards, the number of arimbus and the number of harvestables that remains inside the cutting zone is counted. The factor 'Selectivity' is defined as before. The data are available in Appendix. The equipment worked as expected until it encountered individual arimbus or harvestables.

The test was carried out for 3 subjects. Also, the deflection amount of the stripe is changed. The tested deflections are 5mm, 20mm and 25mm. best results were achieved for deflection of 20mm.



Figure 19 - Testing of prototype 2

3.9.2 Problems encountered

3.9.2.1 Bunch problem

A problem occurred when the prototype encounter a bunch of tea shoots that is packed together. In such instances, there are some arimbus those are located midst other tea shoots. Therefore, the whole bunch gets contact with the stipe at the same time. This will increase the apparent stiffness of arimbus. As a result, when this machine encountered bunches of shoots, all shoots that are in that bunch end up in the cutting zone (no distinction between arimbu and harvestables is made).

3.9.2.2 Short arimbu problem

Although the negative effect is less, there is another problem with this design. Arimbus which are too short slips under the stripe and some of them finds their way to the cutting zone. Therefore, the selection mechanism has failed to select arimbus which are too short. This problem is named ‘the short arimbu problem’.

3.10 Prototype 3

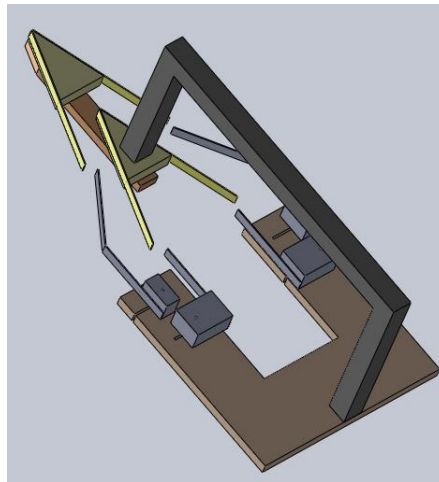


Figure 20 - Prototype 3

Prototype 3 employs a quad-stripe design. This design is implemented in the intention of reducing the ‘bunch problem’. Every tea shoot that gets selected from the first stripe is also tested with the second one. Therefore, even several arimbus get through the first set of stripes; they are supposed to be tested with the second set. At the second set, most of arimbu should be discarded and sent away from the cutting zone.

3.10.1 Testing of prototype 3

The test-procedure is identical to that of the latter one. The results are included in the Appendix. However, prototype 3 did not show any significant improvement over the latter design. Furthermore, the two problems still remained. Beside this design did not (symmetrically) provide an answer to the short arimbu problem.



Figure 21 - Testing of prototype 3

3.11 Including height as a selection criteria

According to the collected data, heights of arimbus and harvestables can be modelled by two normal distributions.

Height of arimbu is approximately $N(78.35, 36.82)$

Height of harvestables is approximately $N(152.7, 47.88)$

N denotes the normal distribution and units of means and standard deviations are in millimetres.

The priority when plucking tea shoots should be given to harvestable shoots. To illustrate, all the harvestable shoots should be plucked. Leaving them on the bush without harvesting will result in an undesirable outcome. That is they will be too matured to be harvested by the time of the next plucking round. On the other hand, harvesting few arimbus will not affect the yield or the bush significantly. Therefore, if a tea plucking machine is to select tea shoots according to their height, it should select almost all the harvestable shoots to be plucked. At the same time, if few arimbus gets selected to be harvested, it will not create much negative effect either on the yield or the bush.

Assume 95% of the harvestable shoots are to be selected by a selection mechanism. As from the normal distribution for harvestable shoots, if all tea shoots that are taller than 74mm are selected, it will select 95% of the harvestable shoots along with 55% of arimbu. In contrast, all the tea shoots that are shorter than 74mm will contain only 5% of harvestable shoots and 45% of arimbu.

Therefore, the mechanism to select shoots according to their height is to select all tea shoots that are taller than 74mm and discard the others without damaging them. Afterwards, the selected shoots will be tested again using some criterion except height to achieve a better selection.

3.12 Prototype 4

3.12.1 Concept

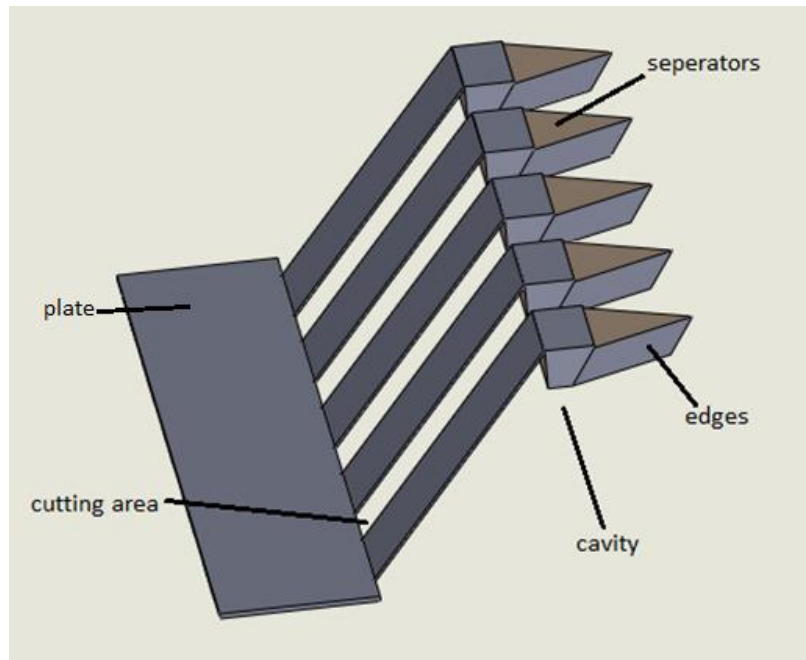


Figure 22 - Concept of prototype 4

The basic construction is as in figure 20. The separators are pushed parallel and 74mm above the plucking table. Short tea shoots go underneath separators into cavities while taller ones hit its edges and slip along. Subsequently, they will find their way into the cutting area. Taller arimbus, as they are less stiff, will hit the edges and bend. Subsequently, they too go into cavities. To produce a complete selecting mechanism, an array of such parts should be connected with each other. This creates another design parameter. That is the distance between two parts. This has to be found experimentally. Mathematical design of the part is as follows.

3.12.2 Mathematical design

Parameters of the prototype to be found analytically

1. Height of the edge from the plucking table
2. Angle of the edges to the horizontal
3. Length of the edge
4. Angle of inclination of the edge to the vertical plane

Height of the edge from the plucking table

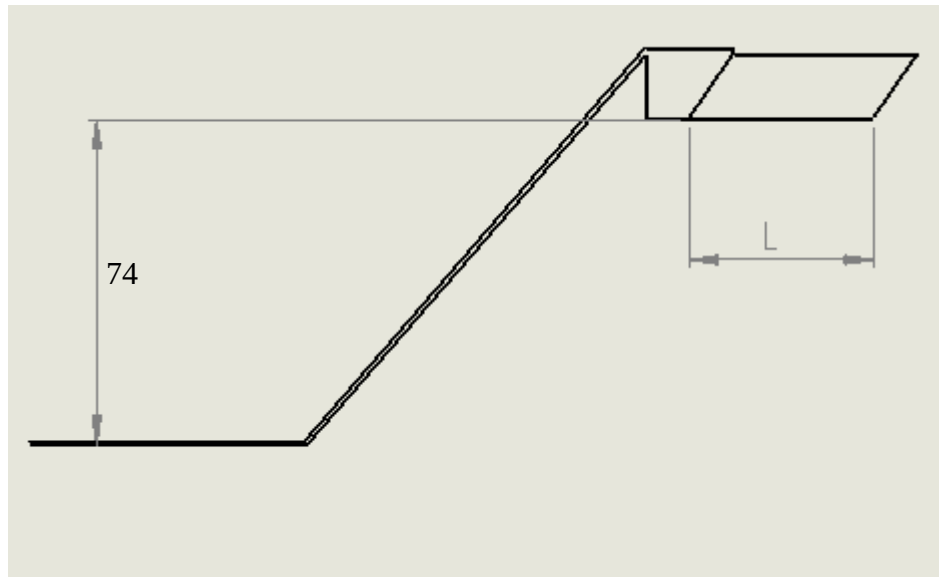


Figure 23 - height of edge from plucking table

As of the section 4.11, the best height for discriminating between the two types of tea shoots is 74 mm. Therefore, 74mm is kept as the height of the edge from the plucking table. Please refer figure 23 for the design. The plate is kept on the plucking table and the mechanism is pushed forward. While doing so, arimbus those come under the separators go inside the cavity. Subsequently, they will be saved from the cutting blades.

The height 74 mm is chosen based on measurements of a tea estate where the tea clone was TRI2026. However, this height might change according many different factors such as tea clone, area where the estate is located, climate, rain fall, sunlight and fertilizers used. Therefore, it is desirables if this height is made adjustable around 74 mm.

Angle of the edges to the horizontal

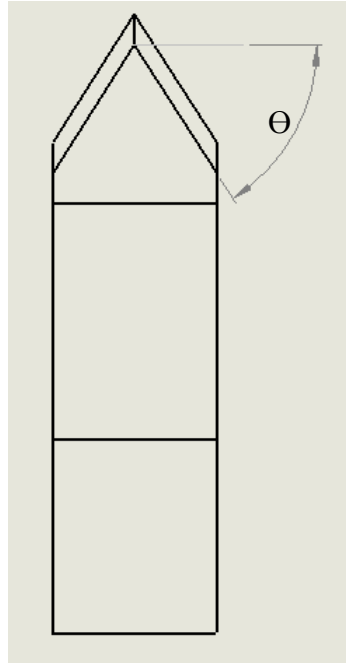


Figure 24 - Angle of the edge to the horizontal

This angle should allow the harvestables to slide along it without undergoing severe bending perpendicular to the edge surface. Hence, all the harvestables go to the cutting area. Arimbus are less in their stiffness than harvestables. Therefore, they will bend and go inside the cavity area.

A mathematical analysis was carried out to find the angle. Aluminium was selected to be used at the edges of separators. This decision was made as it is easily workable. Also, plastic, the earlier material tends to deteriorate at the presence of sunlight over time. For this analysis, coefficient of friction between tea shoots and aluminium was required. Therefore, it was found as before (when finding coefficient of friction between plastic and tea shoots). Data can be found in the appendix section 5.8.

Afterwards, it could be concluded that the angle should be 65° . Please refer appendix for further details of the analysis.

Length of the edges

For this dimension (L), see figure 15. This was assumed to be 50mm when deriving the angle. This was an intuitive decision. Therefore, experimental validation is needed.

Angle of inclination of the edge to the vertical plane (α)

This was assumed to be 20^0 . This too was based on intuition. Therefore experimental validation should be carried out in order to optimise this dimension.

3.12.3 Parameters to be found experimentally

1. Distance between two separators
2. Length of the edges of separators
3. Angle of inclination of the edges to the vertical plane

Distance between two separators

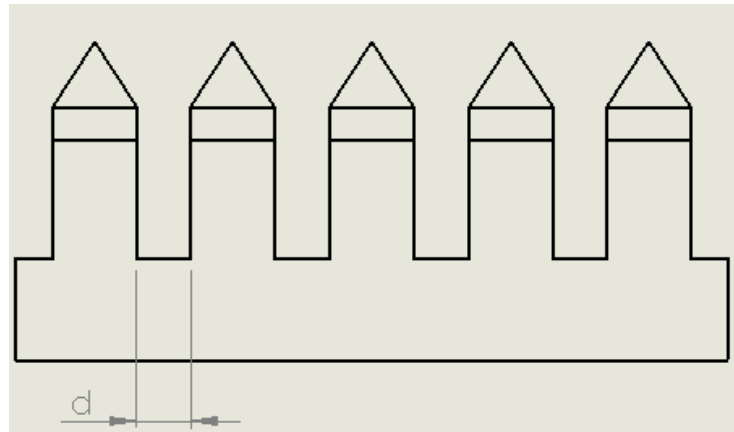


Figure 25 - Distance between separators

In figure 25, the distance between first two separators is shown by 'd'. The selecting mechanism performs the task of selection on a particular tea shoot only if it hits separator edges or if it goes underneath. On the other hand, if a tea shoot goes in between two separators, it does not get tested. Therefore, to increase the ability of selection of the device, the space between two separators should be minimised. Minimising this dimension however may create another problem. It will increase the traffic of tea shoots that goes in between the two separators. This will not only damage tea shoots, but also will make the task of operating the device more cumbersome. This minimum value of d has to be determined experimentally.

3.12.4 The desktop application

Θ depends on three parameters after fixing α . They are L, U (speed of the human operator) and μ (coefficient of friction between shoots and aluminium). During experiments, it is needed to change these dimensions and check the appropriate Θ . To find Θ , a complex

equations have to be solved (refer appendix). This is very time consuming. Therefore, a desktop application was developed to do the task. Matlab was used for the purpose.

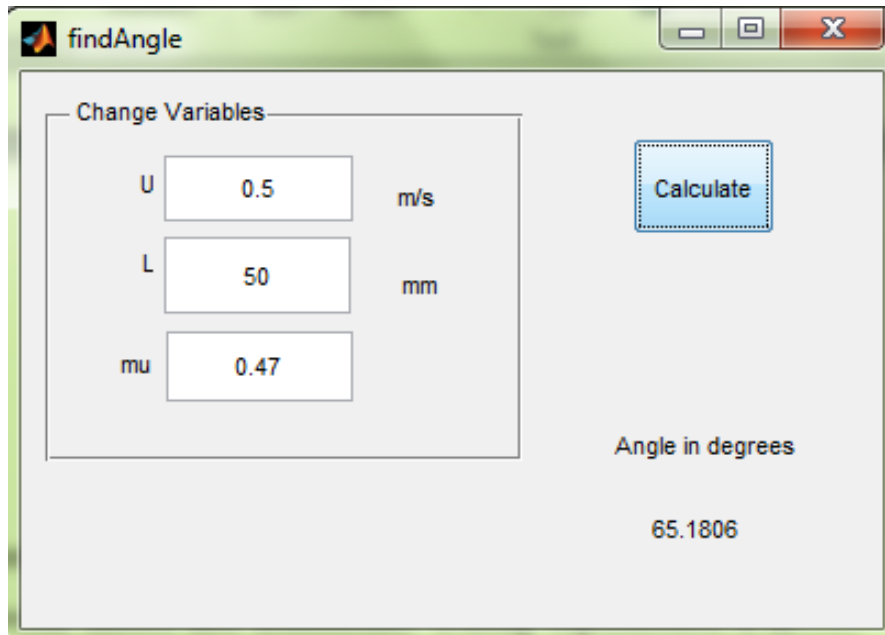


Figure 26 - Application to find Θ

The values for U, L, and μ (μ) can be set in the text boxes. By clicking calculate button, the respective Θ can be calculated in degrees as shown in figure 26

3.12.5 Construction of prototype 4

Main objectives of constructing and testing prototype 4 are

1. Check whether the selection mechanism works
2. Obtain the minimum distance between two separators that will allow proper operation of the device

The main structural material used is wood. This material was used because it is easily workable.

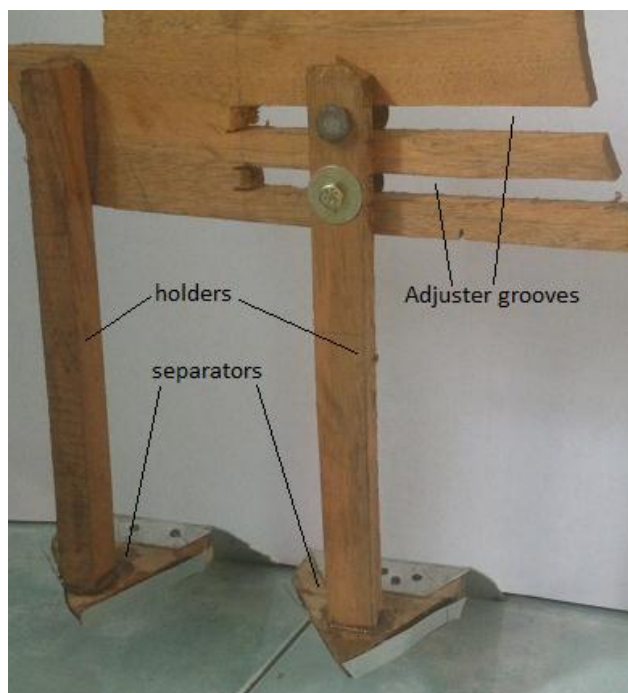


Figure 27 - Prototype 4

The construction consists of two separator parts. To obtain the minimum distance between separators, the distance should be adjustable. To provide this adjustability, two adjuster grooves were provided as shown in figure 27.

3.12.6 Testing of prototype 4

The prototype was tested on field (refer figure 28). With the testing, it could be concluded that a distance of 35mm between two parts will be enough.



Figure 28 – Verification of prototype 4 design

Problems faced

- Tea shoots which arrive between the separators does not get selected. Therefore, all such shoots arrive into the cutting zone regardless they are harvestables or arimbus

- Occasionally, some harvestables too, get bent and go inside the cavity under the separators. In order to overcome this, a second sweep of the mechanism over the plucking bed may be required.

4. ASSEMBLY

4.1 Final design

Prototype 4 can be easily attached to an existing tea harvesting machine. To do so, an appropriate machine should be selected.

Ochiai AM-110VB450 tea harvester is one of the mostly used machines in Sri Lanka. This machine however, harvests tea shoots in a non-selective way. It can be improved if a selection mechanism is attached to it.

4.1.1 Details about Ochiai AM-110VB450 machine



Figure 29 - Ochiai AM-110VB450 machine (source: [42])

- Power source - IC engine
 - 2 stroke
 - 25 cc
- Fuel – gasoline and oil mixture 25:1
- Weight – TO DO
- Blade
 - Length - 600mm
 - Type – reciprocating double blades
- Collecting the yield
 - Blower blows shoots into a sack

Operation

- IC engine is started by pulling the starting string
- The engine powers blades and a blower
- The machine should be kept on the plucking bed and be pushed forward
- Tea shoots gets harvested by blades
- There are vents that blow air to push the harvested tea shoots into a sack
- Yield gets collected inside a sack

4.1.2 Material selection

The main structural material used is Al. there are several reasons behind this selection. They are as follows

- Al is light and strong
- Easily workable
- Corrosion resistant

Wood was used at as the material for separator parts since it can be easily worked and can be attached to Al frame easily.

4.1.3 Attaching the prototype 4 to Ochiai AM-110VB450

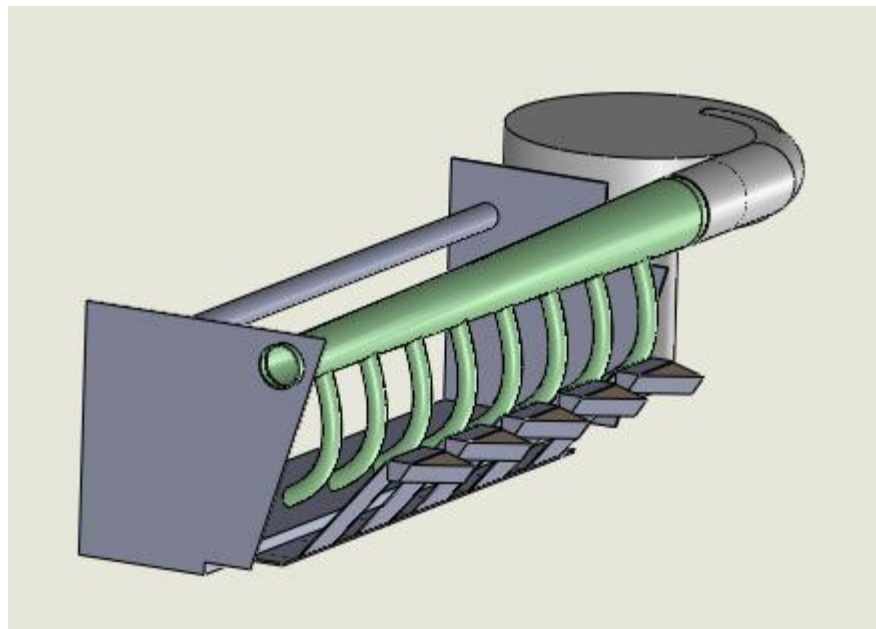


Figure 30 - Prototype 4 attached to existing machine

As shown in Figure 30, the selection mechanism can be attached to the existing machine.



Figure 31 - Tea harvester machine with the attachment

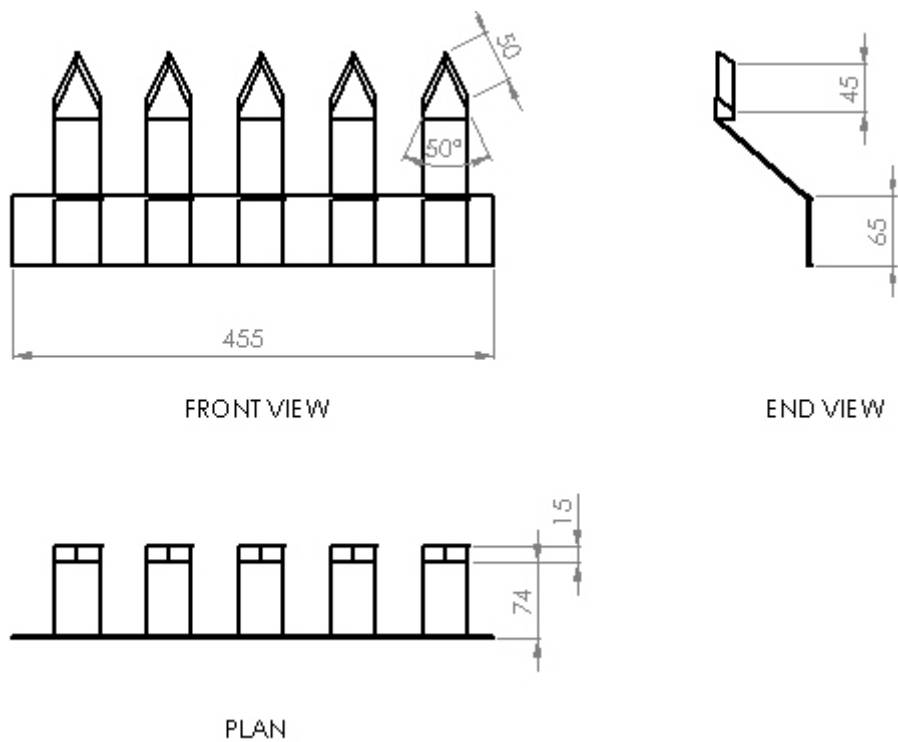


Figure 32 – Drawing of the mechanism

Weighing of machine components

Table 6 - Weighing of machine components

Machine component	Weight (g)
Ochiai AM-110VB450 (with sack)	1800
Selecting mechanism	620
fixtures	200
total	2620

5. EVALUATION

5.1.1 Testing

The prototype was tested in a tea estate. The tea clone was TRI2026. Testing was performed on 3 tea bushes. The numbers of arimbus and harvestables before harvesting were counted. Similarly, the numbers after harvesting too were counted.



Figure 34 - Before harvesting



Figure 33 - After harvesting



Figure 35 -Testing the final design

5.1.2 Results

The following table shows the average numbers of arimbus and harvestables, before and after harvesting.

Table 7 – Results of testing the final design

	Harvestables	Arimbus
Before harvesting	11	31
After Harvesting	0	20

By examining the results, it can be seen that 65% of arimbus can be saved. Subsequent observation on the factor of selectivity would be appropriate in order to compare results with the previous designs.

Selectivity = 44.2

This value is greater than the previous designs. Therefore, it can be concluded that prototype 4 is the most superior one tested yet.

5.1.3 Problems

Although the triangular parts are designed in such a way that all the harvestables will be deflected and get into the cutting area, some harvestables tend to bend and crawl under the part. This can be seen when there are harvestables which are initially deflected. Such harvestables are mostly seen at the edges of the bush. Therefore, they will remain on the bush after the machine moves across the bush. To harvest them, a second run of the machine on the bush is required. However, doing so will harvest more arimbus. This is not desirable. Therefore, the mechanism should be improved so that it would get all the harvestables into the cutting area at the very first sweep of the bush.

6. CONCLUSIONS

6.1 Summary

Firstly, context of local tea industry is studied. It is seen that proper mechanisation of tea harvesting using a selective tea harvesting mechanism will significantly improve the

performance of tea industry in the island. As a first step, the mechanism could concentrate on harvesting all mature tea shoots while leaving immature ones intact.

Electronic methods of achieving selection were ruled out since they have significant drawbacks. Mechanical selection methods are selected as the path to follow. To achieve selection by mechanical means, two characteristics of tea shoots can be used. They are stiffness and height. Three prototypes to select tea shoots based on their stiffness were tested on field. Even though they could achieve a moderate degree of selectivity, there were some drawbacks. Afterwards, height too was included for the method for discriminating tea shoots. A prototype was fabricated to test the concept. The results were superior to previous ones.

An index for measuring selectivity levels of tea harvesting methods was developed. This index can be used to evaluate and compare performance of various selection methods.

A modified prototype could be easily attached to an existing tea harvesting machine. Therefore, an existing machine was tested in field with the fabricated attachment. Results were successful. It saved approximately 65% of immature tea shoots intact on the bush on average.

Even though this is a significant achievement, still there is plenty of for improvement. Possible improvements are also discussed in this report.

6.2 Future works

The dimensions of the final prototype are based on mathematical calculations with some intuition. Therefore, they may not be the optimum dimension in practical situation. Optimum dimensions have to be found experimentally. Mathematical values can be kept as a guideline and experimentation can be performed by changing the dimensions around mathematical values. Practical optimum dimensions will further improve the selectivity of the mechanism.

There is no selection between two separators. Hence, Performance of the machine is reduced. Therefore a selection mechanism such as prototype 2 can be attached in the gap between two separators.

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APPENDIX A

Height of tea shoots

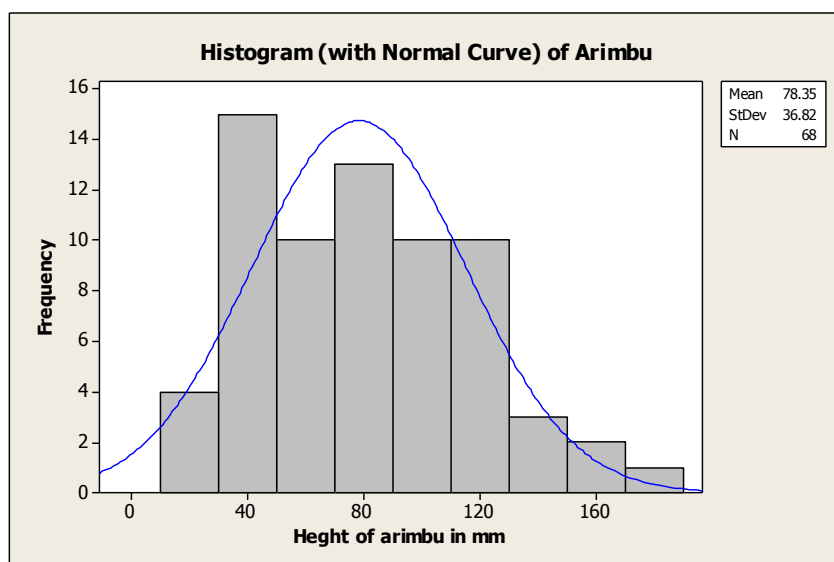
The following tables show the data collected in a tea estate in Attanagalla. The data sets represent heights of arimbu and harvestable tea shoots in millimetres. The heights were measured from the plucking table to the start of the top most bud.

Height of arimbu

51	116	110	32	69	135	85	70
86	40	70	121	93	100	65	152
43	154	112	40	55	65	115	55
111	142	110	35	45	85	25	62
109	108	113	45	47	70	19	30
138	82	115	30	110	106	29	106
68	75	182	55	72	70	35	92
70	34	25	40	80	62	95	81
100	38	42	106				

Descriptive Statistics: Arimbu

Variable	Mean	SE Mean	StDev	Variance	CoefVar	Minimum	Maximum
Arimbu	78.35	4.46	36.82	1355.55	46.99	19.00	182.00

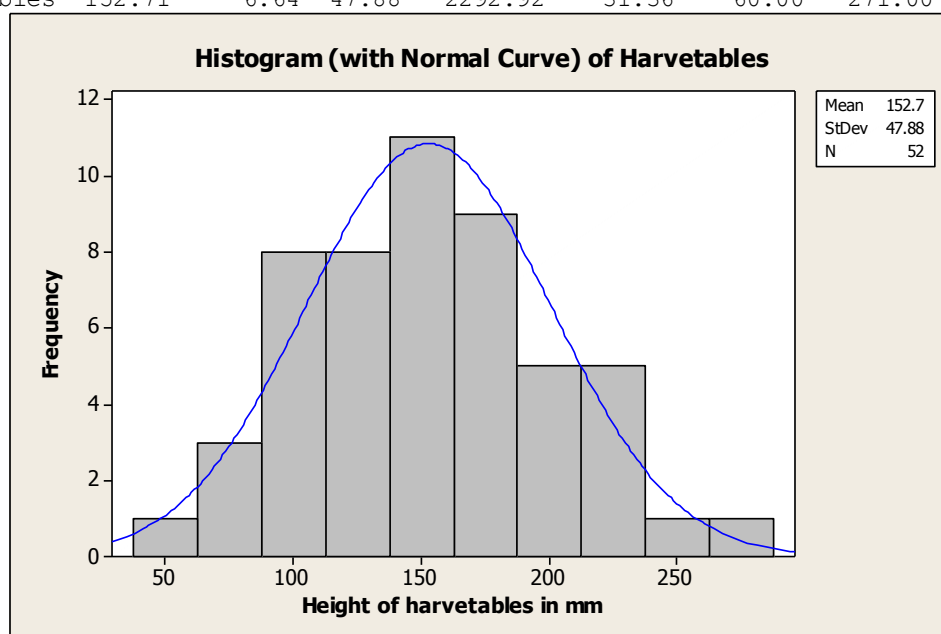


Height of harvestable tea shoots

194	135	176	110	160	271	165
182	130	146	100	145	187	155
226	110	132	105	170	216	140
243	120	156	75	120	211	160
190	95	164	95	125	190	75
176	221	202	145	60	230	110
100	150	215	115	125	180	65
150	141	182				

Descriptive Statistics: Harvetables

Variable	Mean	SE Mean	StDev	Variance	CoefVar	Minimum	Maximum
Harvetables	152.71	6.64	47.88	2292.92	31.36	60.00	271.00



Testing for difference of height between the two populations of harvestables and arimbus

Table 8 – height statistics of tea shoots

	Arimbu	Harvestables
Mean height/cm	78.35	152.7
Standard Deviation/cm	36.82	47.88

In order to determine how different the two means of the two populations of heights of arimbus and that of harvestable shoots, a T test for difference between two populations is performed.

$$T = \frac{152.7 - 78.35}{\sqrt{\frac{47.88^2}{52} + \frac{36.82^2}{68}}}$$

= 135.13

$$\text{Degrees of freedom} = \frac{\frac{36.82^2}{68} + \frac{47.88^2}{52}}{\frac{\left(\frac{36.82^2}{68}\right)^2}{67} + \frac{\left(\frac{47.88^2}{52}\right)^2}{51}}$$

=93

P-value = 0.00

Therefore, the two population means are significantly different.

Determining the spring coefficient of the spring

Table 9 - Stiffness of spring - data

F (g)	X (mm)
0	0
4	2
7	5
12	7
16	9
21	11
24	12
28	14
31	15

Regression Analysis: F versus X

The regression equation is
 $F = -1.36 + 2.07 X$

Predictor	Coef	SE Coef	T	P
Constant	-1.3586	0.8725	-1.56	0.163
X	2.06970	0.09005	22.98	0.000

S = 1.33560 R-Sq = 98.7% R-Sq(adj) = 98.5%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	942.40	942.40	528.30	0.000

Residual Error	7	12.49	1.78
Total	8	954.89	

Durbin-Watson statistic = 1.08664

Therefore, spring constant = 2.07 g/mm

Measuring force required to deflect tea shoots

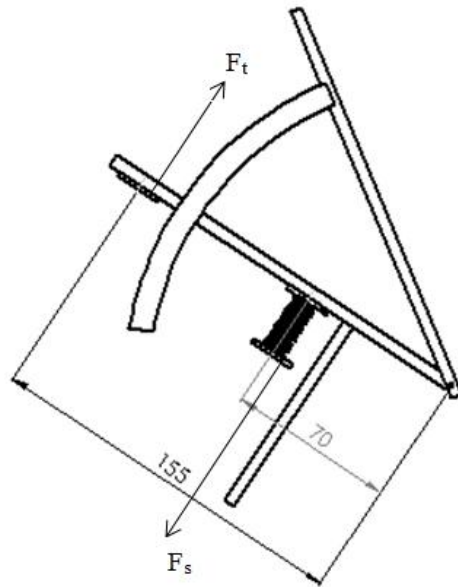


Figure 36 – Equipment for measuring stiffness of tea shoots

Let the force applied at the spring is F_s and the force that is given by the shoot against the pull of the lower arm is F_t .

$$F_s * 70 = F_t * 155$$

$$F_t = 0.4516F_s$$

Let Θ be the angle between the two arms. The deflection length of the shoot at the plate is approximately equal to 2.7Θ .

Deflection of spring was taken at different heights measured from the plucking table. Data for 15 harvestable shoots and 10 arimbus are taken (Refer appendix).

Using these data, two linear multiple regression models were built for harvestable tea shoots and arimbu using two predictors and one response variable. Predictors are height

from plucking table (h) and deflection (distance) (x). The response variable is force required to deflect the tea shoot.

According to the linear multiple regression model, force required to deflect harvestable tea shoots,

$$F_h = 4.74 + 0.117x - 0.0257h$$

This equation is valid for $50 < h < 185$ and $13.55 < x < 40.65$

Force required for deflecting arimbu,

$$F_a = -0.749 + 0.0282h + 0.103x$$

This equation is valid for $40 < h < 70$ and $13.55 < x < 40.65$

Both h and x are in millimetres.

$$F_h - F_a = 5.489 - 0.0539h + 0.014x$$

For the selection procedure to be easy, $F_h - F_a$ value must be a maximum so that the selection mechanism can identify the shoot type easily. For this to happen h should be as low as possible while x should be as high as possible.

Lowest possible value for h is zero. But this will increase the collisions of mature leaves of the tea bush with the selection mechanism. Therefore, $h=10\text{mm}$ will be used. x is kept as a variable, so that it can be adjusted in the machine to achieve good selectivity in various tea estates and cultivars.

By the statistical analysis done previously, it can be concluded that stiffness values of two populations are significantly different. Therefore, stiffness can be used as a selection criterion.

Let the selectivity is done at the average value of F_a and F_h . That is at

$$[F_h(x, h=10) + F_a(x, h=10)]/2$$

$$= 2.008 + 0.11x$$

This value changes as x is varied.

Force required to deflect tea shoots - analysis

In following data tables, h is the height from plucking table to the point of shoot where the measurement is taken. X is the deflection distance of the measured point from neutral position. F is the force that is required to deflect the shoot as described.

Table 10 - Data for harvestable tea shoots

h(mm)	x(mm)	f(g)	h(mm)	x(mm)	f(g)	h(mm)	x(mm)	f(g)
50	13.55	4.67406	50	40.65	9.34812	145	27.1	3.73925
80	13.55	5.60887	90	40.65	6.54368	160	27.1	3.67406
90	13.55	4.67406	50	40.65	9.34812	160	27.1	2.80444
50	13.55	3.73925	60	40.65	7.4785	135	27.1	3.73925
110	13.55	4.67406	50	40.65	9.34812	185	27.1	3.67406
60	13.55	3.73925	55	40.65	9.34812	150	27.1	3.73925
50	13.55	4.67406	60	40.65	6.54368	120	27.1	4.67406
55	13.55	3.73925	50	40.65	9.34812	155	27.1	4.17406
70	13.55	4.67406	70	40.65	8.41331	185	27.1	3.73925
65	13.55	3.73925	145	13.55	2.80444	155	27.1	4.47406
90	13.55	4.67406	160	13.55	2.80444	160	27.1	3.73925
60	13.55	3.73925	160	13.55	1.86962	140	27.1	3.93925
70	13.55	5.60887	135	13.55	1.86962	135	27.1	4.67406
50	27.1	7.4785	185	13.55	1.86962	145	40.65	5.67406
90	27.1	5.60887	150	13.55	1.86962	160	40.65	5.60887
50	27.1	6.54368	120	13.55	2.80444	135	40.65	5.67406
110	27.1	6.54368	155	13.55	3.73925	185	40.65	5.60887
60	27.1	5.60887	185	13.55	1.86962	150	40.65	4.67406
50	27.1	7.4785	155	13.55	2.73925	120	40.65	5.60887
55	27.1	5.60887	160	13.55	2.80444	155	40.65	4.97406
65	27.1	6.54368	140	13.55	1.86962	185	40.65	4.67406
60	27.1	5.67406	140	13.55	3.73925	155	40.65	5.60887
50	27.1	6.54368	135	13.55	2.80444	160	40.65	4.67406
70	27.1	6.54368	140	13.55	2.80444	140	40.65	5.67406
						140	40.65	6.54368
						135	40.65	5.60887
						140	40.65	4.87406

Table 11 - Data for Arimbu

h(mm)	x(mm)	f(g)	h(mm)	x(mm)	f(g)
65	13.55	1.869624	60	27.1	3.739248
45	13.55	1.869624	60	27.1	3.739248
60	13.55	2.804436	70	27.1	3.739248
40	13.55	1.869624	65	27.1	4.67406
55	13.55	1.869624	65	40.65	5.608872
60	13.55	1.869624	45	40.65	4.67406
60	13.55	2.804436	60	40.65	4.67406
70	13.55	1.869624	40	40.65	4.67406
65	13.55	2.804436	55	40.65	4.67406
65	27.1	4.67406	60	40.65	5.608872
45	27.1	2.804436	60	40.65	4.67406
60	27.1	4.67406	70	40.65	4.67406
55	27.1	3.739248	65	40.65	5.608872

Model for the harvestable tea shoots

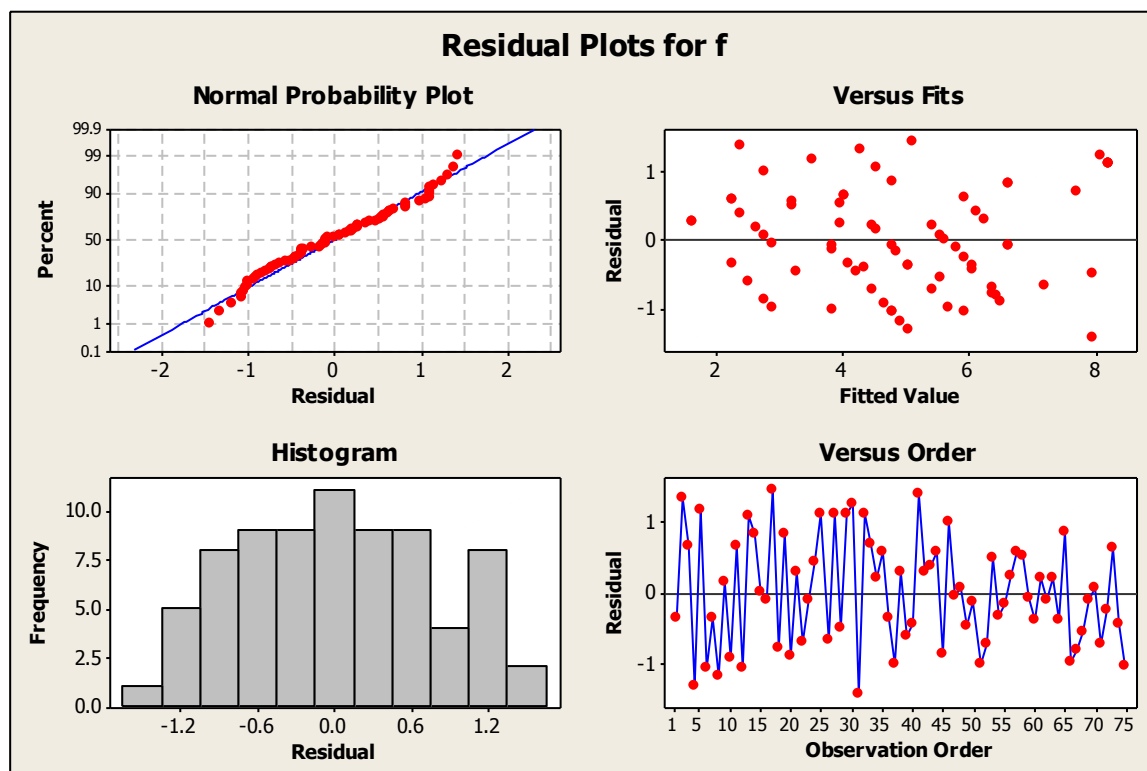
Stepwise Regression: f versus x, h

Alpha-to-Enter: 0.05 Alpha-to-Remove: 0.05

Response is f on 2 predictors, with N = 75

Step	1	2
Constant	1.877	4.743
x	0.1159	0.1174
T-Value	7.87	14.89
P-Value	0.000	0.000
h		-0.0257
T-Value		-13.51
P-Value		0.000
S	1.42	0.761
R-Sq	45.88	84.70
R-Sq (adj)	45.14	84.27
Mallows Cp	183.6	3.0

By looking at the above results, it can be concluded that both x and h are significant for the model (both p values are less than 0.05)



By looking at residual histogram, it can be seen that residuals are approximately normally distributed with a mean value of zero. From the residual vs. fitted value plot, it can be observed that residuals are randomly distributed. Therefore, it is appropriate to use the standard multivariate linear regression for modelling the harvestable tea shoots.

Regression Analysis: *f* versus *x*, *h*

The regression equation is

$$\hat{f} = 4.74 + 0.117 x - 0.0257 h$$

Predictor	Coef	SE Coef	T	P	VIF
Constant	4.7433	0.3089	15.36	0.000	
<i>x</i>	0.117412	0.007886	14.89	0.000	1.000
<i>h</i>	-0.025653	0.001899	-13.51	0.000	1.000

S = 0.760549 *R*-Sq = 84.7% *R*-Sq(adj) = 84.3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	230.48	115.24	199.22	0.000
Residual Error	72	41.65	0.58		
Total	74	272.12			

Source	DF	Seq SS
<i>x</i>	1	124.86

h 1 105.61

Durbin-Watson statistic = 2.48952

Randomness of the residuals are further supported by the fact that Durbin-Watson statistic being close to 2 (2.49). Furthermore, the model can describe almost 85% variance of the actual data. With these observations, it is appropriate to use this mathematical model to describe the deflection of harvestable tea shoots.

Model for arimbu

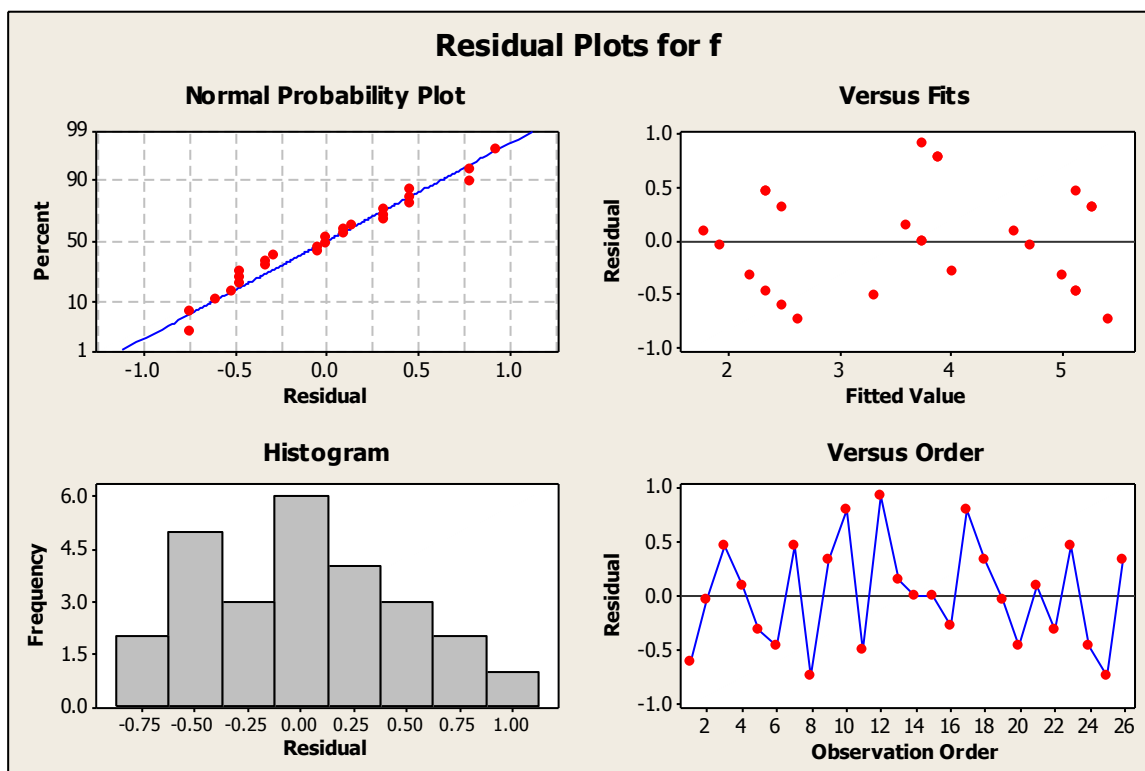
Stepwise Regression: f versus h, x

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is f on 2 predictors, with N = 26

Step	1	2
Constant	0.8989	-0.7493
x	0.1035	0.1035
T-Value	10.72	11.79
P-Value	0.000	0.000
h		0.028
T-Value		2.46
P-Value		0.022
S	0.555	0.504
R-Sq	82.72	86.32
R-Sq (adj)	82.00	85.13
Mallows Cp	7.1	3.0

By looking at the above results, it can be concluded that both x and h are significant for the model (both p values are less than 0.05)



By looking at residual histogram, it can be seen that residuals are approximately normally distributed with a mean value of zero. From the residual vs. fitted value plot, it can be observed that residuals are randomly distributed. Therefore, it is appropriate to use the standard multivariate linear regression for modelling arimbu.

Regression Analysis: f versus h, x

The regression equation is
 $f = -0.749 + 0.0282 h + 0.103 x$

Predictor	Coef	SE Coef	T	P	VIF
Constant	-0.7493	0.7177	-1.04	0.307	
h	0.02819	0.01146	2.46	0.022	1.000
x	0.103485	0.008775	11.79	0.000	1.000

S = 0.504483 R-Sq = 86.3% R-Sq(adj) = 85.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	36.933	18.466	72.56	0.000
Residual Error	23	5.854	0.255		
Total	25	42.786			

Source	DF	Seq SS
h	1	1.541
x	1	35.392

Durbin-Watson statistic = 2.40944

Randomness of the residuals are further supported by the fact that Durbin-Watson statistic being close to 2 (2.41). Furthermore, the model can describe more than 86% variance of the actual data. With these observations, it is appropriate to use this mathematical model to describe the deflection of arimbu.

Testing for difference of stiffness of the two populations (arimbus and harvestables)

By analysing data for deflection of harvestables, statistics of the force required to deflect a harvestable tea shoot are as follows (at a height of 10mm and when deflected by 20mm)

Prediction mean = 5.4 g

Prediction standard error = 0.234

Statistics for arimbu at height = 10mm and deflection = 20mm are shown below.

Prediction mean = 1.6 g

Prediction standard error = 0.567

Subsequently, a T test is performed to test the difference of mean values

$$T = \frac{5.4 - 1.6}{\sqrt{\frac{0.234^2}{75} + \frac{0.567^2}{26}}}$$

= 33.207

$$\text{Degrees of freedom} = \frac{\left(\frac{0.234^2}{75} + \frac{0.567^2}{26}\right)^2}{\frac{\left(\frac{0.234^2}{75}\right)^2}{74} + \frac{\left(\frac{0.567^2}{26}\right)^2}{25}}$$

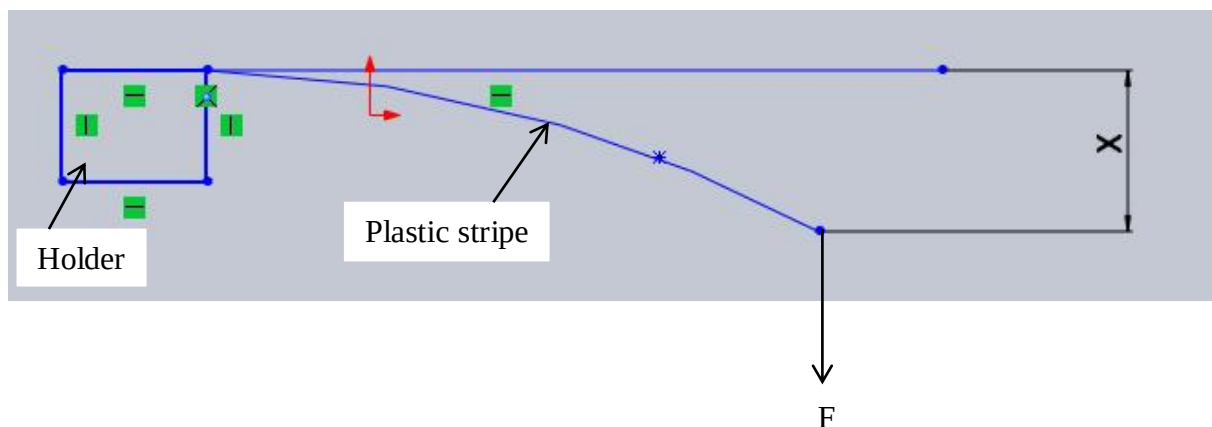
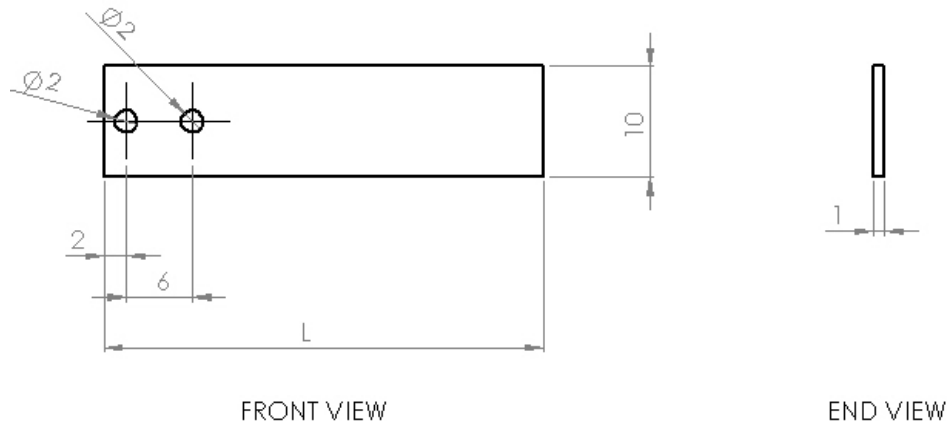
=28

P-value = 0.00

Therefore, two population means are significantly different.

Plastic stripe

The stiffness values of such plastic stripes of varying lengths were measured using custom-made equipment.



Various weights are attached at the end of the stripe and the deflection X is measured.

Theoretical formula for bending of beams gives the following.

$$F = (3.058 * 10^3 EI) * \left(\frac{x}{L^3 * \cos \theta} * 10^5 \right)$$

Where F = force applied at the free end of the stripe. This is measured in grams

L = length of the stripe

θ = angle of inclination of the stripe

x = vertical deflection of the stripe at the free end. This is measured in mm

E = linear elasticity modulus of plastic material

I = 2nd moment of area of cross section of the stripe

Above equation is taken as $F = kY$

Where $k = (3.058 * 10^3 EI)$

And $Y = (\frac{x}{L^3 * \cos\theta} * 10^5)$

Here, E and I are measured in SI units where x and L are in mm.

A regression model was built to find the values of k. For information about the data and regression, see the appendix section 5.5. Following equation models the force required to bend the plastic stripe.

$$F = -0.282 + 0.513 Y$$

Where F is the force and it is in grams. Y is the amount of deflection and it is in mm.

Then, it can be concluded that $k=0.513 \text{ gmm}^{-1}$

Simple verification to check whether this stripe is suitable for the task of selection

The selection of shoots are done at a force of $2.008 + 0.11 x$. Assume $x=10\text{mm}$. The force required = 3.1 g. This force is applied on the stripe when it selects the critical tea shoot.

From the equation for the plastic stripe,

$$F = -0.282 + 0.513 Y$$

Here, $Y = \frac{x}{L^3 * \cos\theta} * 10^5$ and $F = 3.1 \text{ g}$

$$L^3 \cos\theta = 152 * 10^3$$

This equation yields an infinite number of (L, θ) pairs. One possible value is $\theta=45^\circ$ and $L=60\text{mm}$.

Data

F(g)	Y(mm)	F(g)	Y(mm)	F(g)	Y(mm)
0	0	0	0	0	0
1	3.4195	1	3.5037	1	3.58436
2	5.02483	2	4.97778	2	4.77915

3	6.3275	3	6.87407	3	6.87654
4	7.816	4	8.2963	4	8.16872
5	9.14167	5	9.48148	5	10.3635
6	11.1187	6	11.4296	6	12.5583
7	13.77	7	13.0296	7	14.6557
0	0	0	0	0	0
1	3.14156	1	3.33249	1	2.80026
2	5.29105	2	5.77665	2	5.02891
3	6.61381	3	6.98012	3	7.14323
4	7.60588	4	7.94289	4	9.37187
5	9.43261	5	9.14636	5	11.6005
6	11.094	6	11.8684	6	12.7148
7	13.4247	7	13.8312	7	14.8292
0	0	0	0	0	0
1	2.25269	1	3.5315	1	3.17476
2	4.67866	2	5.05399	2	5.5104
3	6.23821	3	7.06299	3	6.67822
4	7.10463	4	8.32424	4	9.01387
5	9.62448	5	9.82874	5	10.1817
6	11.1443	6	11.5855	6	13.3495
7	15.0108	7	13.09	7	14.5173
0	0	0	0	0	0
1	3.00838	1	3.37931	1	3.60297
2	4.32455	2	5.74785	2	5.40446
3	5.82874	3	7.11638	3	7.67162
4	8.76886	4	7.6638	4	9.20594
5	9.33293	5	9.75862	5	11.4731
6	11.709	6	11.8535	6	12.4731
7	13.8371	7	13.1272	7	15.0074
0	0	0	0	0	0
1	2.9759	1	2.33202	1	3.59529
2	4.46385	2	4.49804	2	5.02783
3	5.73923	3	7.1169	3	7.89293
4	7.58949	4	7.73576	4	9.32548
5	9.22718	5	9.66405	5	9.19057
6	11.8649	6	11.2829	6	13.6231
7	13.0774	7	13.5923	7	15.0557
0	0	0	0	0	0

1	3.29322	1	3.42518	1	3.53623
2	4.30651	2	4.26901	2	5.24347
3	5.57313	3	7.00654	3	6.95072
4	7.07978	4	7.74407	4	8.36521
5	9.83976	5	9.85036	5	11.0725
6	11.3464	6	11.2191	6	12.7797
7	13.5997	7	13.3254	7	15.487
0	0	0	0	0	0
1	3.25668	1	2.26669	1	3.97398
2	4.55935	2	4.16299	2	5.16878
3	5.21069	3	7.58522	3	6.36358
4	7.86202	4	8.05929	4	9.55837
5	11.839	5	9.00745	5	11.5584
6	12.4904	6	9.48152	6	12.7532
7	13.1417	7	13.4297	7	15.948

Regression analysis

Regression Analysis: F versus Y

The regression equation is
 $F = -0.282 + 0.513 Y$

Predictor	Coef	SE Coef	T	P	VIF
Constant	-0.28197	0.06259	-4.51	0.000	
Y	0.512694	0.007288	70.35	0.000	1.000

S = 0.415274 R-Sq = 96.8% R-Sq(adj) = 96.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	853.37	853.37	4948.46	0.000
Residual Error	166	28.63	0.17		
Total	167	882.00			

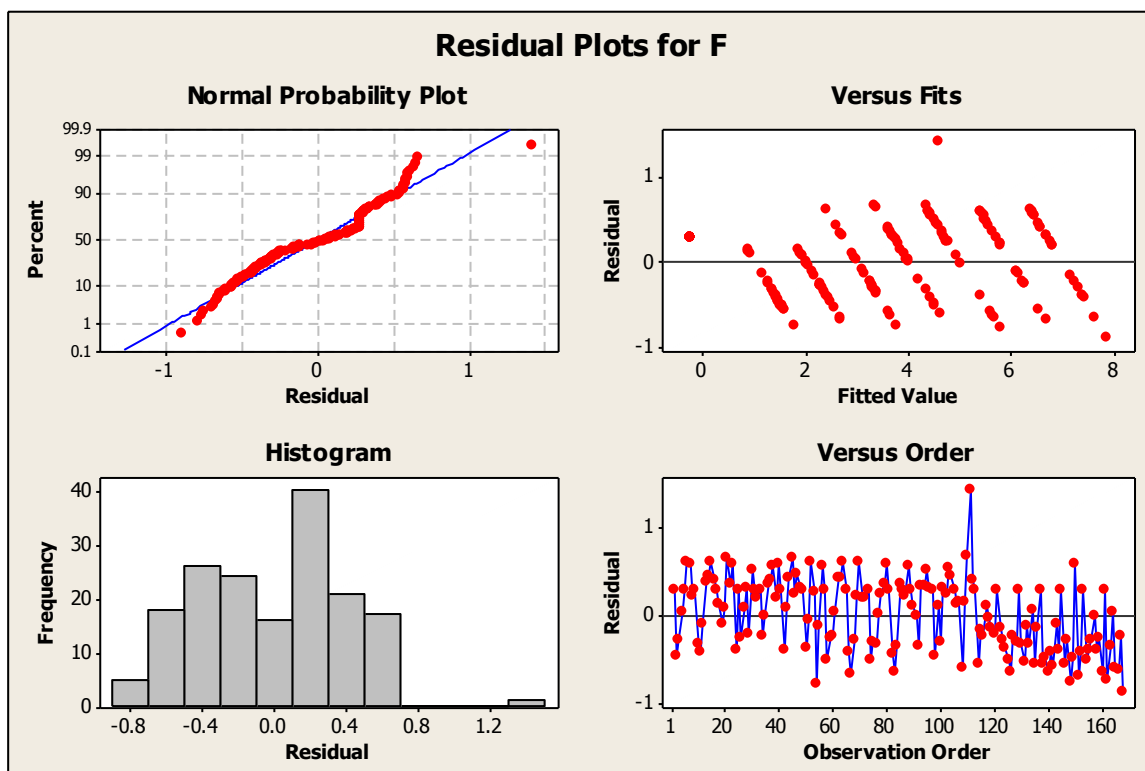
Unusual Observations

Obs	Y	F	Fit	SE Fit	Residual	St Resid
111	9.5	6.0000	4.5791	0.0355	1.4209	3.43R
168	15.9	7.0000	7.8945	0.0702	-0.8945	-2.19R

R denotes an observation with a large standardized residual.

Durbin-Watson statistic = 1.19881

Residual Plots for F



The histogram of residuals shows that they are approximately normally distributed. Randomness is moderate with a Durbin-Watson statistic of value 0.9. To conclude, the regression equation is

$$F = -0.282 + 0.513 Y$$

Where F is the force and it is in grams. Y is the amount of deflection and it is in mm.

Design of the plastic stripe

Avoid tea shoots from bending

Initial part of the plastic stripe (closer to the pivot edge) is very high in its stiffness. Therefore, it can be considered to be rigid. Arimbu is less in stiffness than the harvestable shoots. Therefore, if arimbus do not bend, the others do not. Hence, the stiffness of arimbu has been used in the following derivation. It is also assumed that the coefficient of friction of arimbu equals that of harvestable tea shoots. No impact forces are assumed that arise because of the contact between a shoot and the stripe.

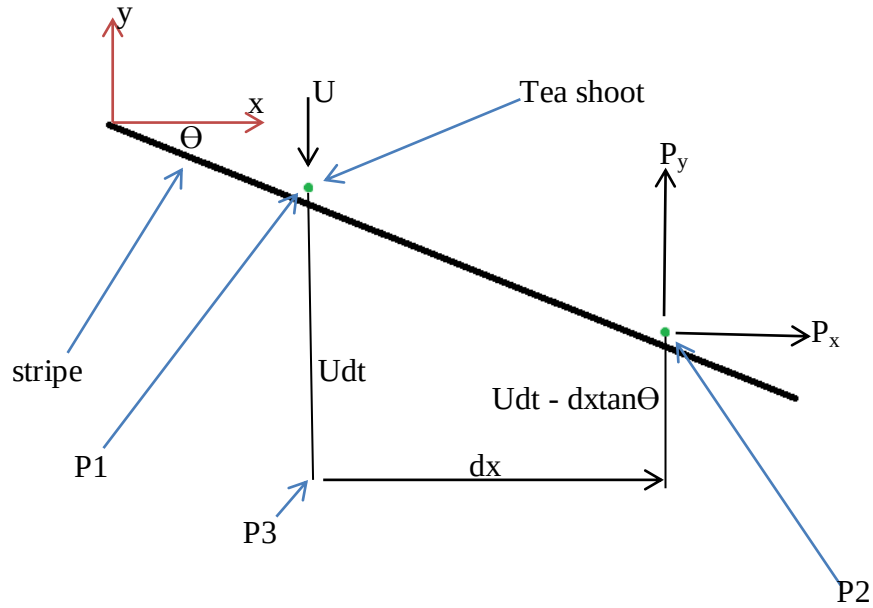


Figure 37 - plastic stripe and a tea shoot

Suppose that the stripe is moving towards a tea shoot at velocity u . Without any loss of generality, it can be assumed that the shoot is moving towards the stripe while the latter is being stationary. The shoot makes its initial contact with the stripe at point P1. Afterwards, assume it slides along the stripe to the point P2 without bending excessively and crawling under the plastic stripe (assumed to be rigid).

If there was no stripe to obstruct the advance of the tea shoot, it would have ended at point P3 after a time interval of dt . However, as the stripe blocks its advance, it has to stop at point P2. Therefore, the deformation of the shoot in direction y is $Udt - dx \tan \Theta$. Likewise, there is a deformation of dx in the direction of x .

From the deformation-model for arimbu, we have

$$F_a = -0.749 + 0.0282 h + 0.103 x$$

, where F_a is the force required to make a deformation of x (mm) of an arimbu h (mm) above the plucking table. Assume $h = 10\text{mm}$.

$$F_a = -0.467 + 0.103x$$

Consider the deformation in y direction. Deformation in that direction is $Udt - dx \tan \Theta$. Then the equation becomes

$$P_y = 0.103 (Udt - dxtan\Theta) - 0.467$$

Next consider the deformation in x direction. The deformation is dx in this direction. Therefore, the equation becomes,

$$P_x = 0.103 dx - 0.467$$

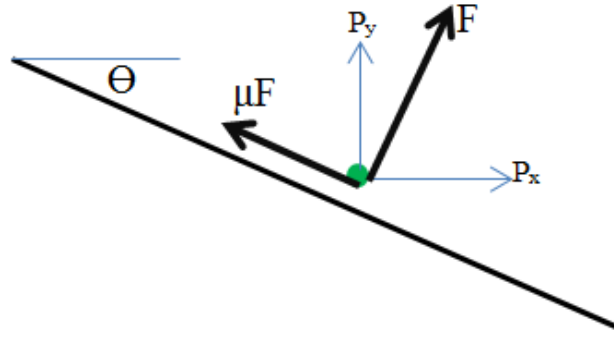


Figure 38 - Friction forces

Due to the rubbing of the tea shoot against the stripe, friction forces are formed as shown in figure 6. These are named F (normal force) and μF (friction force). These forces combine to provide the forces P_x and P_y .

$$F = P_y \cos\Theta + P_x \sin\Theta$$

$$= [0.103 (Udt - dxtan\Theta) - 0.467] \cos\Theta + [0.103 dx - 0.467] \sin\Theta$$

$$\mu F = P_y \sin\Theta - P_x \cos\Theta$$

$$= [0.103 (Udt - dxtan\Theta) - 0.467] \sin\Theta - [0.103 dx - 0.467] \cos\Theta$$

$$\frac{\mu F}{F} = \mu$$

$$[0.103 (Udt - dxtan\Theta) - 0.467][\sin\Theta - \mu \cos\Theta] = [0.103 dx - 0.467][\mu \sin\Theta + \cos\Theta] \text{ -----(1)}$$

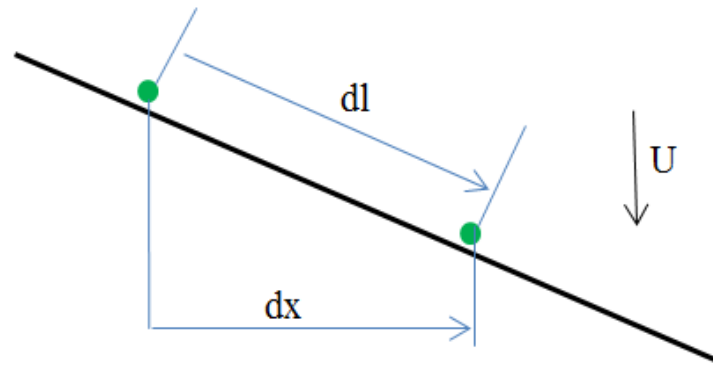


Figure 39 - sliding of shoot along the stripe

As shown in figure 7, the shoot slides along the stripe. In a time period of dt , it will travel a distance dl along the stripe. For not to bend and not to crawl under the stripe in y direction, the shoot should move in the $-y$ direction at a velocity of U .

Therefore, $dl \sin\theta = Udt$.

But, $dl = dx/\cos\theta$

Therefore,

$$dx \tan\theta = Udt$$

Substitute in equation 1 and letting $dx \rightarrow 0$

$$\sin\theta - \mu\cos\theta = \mu\sin\theta + \cos\theta$$

$$\tan\theta = \frac{1+\mu}{1-\mu}$$

According to the experiment 3, $\mu = 0.54$

Therefore, $\theta = 73^\circ$

Let $\theta = 70^\circ$ for further usages.

However, the equations for F_a and F_h which were used here are only valid for $13.55 < x < 40.65$ mm. Nevertheless these were used to extrapolate the values while x lies beyond the range. Therefore, experimental verification of the result is necessary.

Maximising the deflection

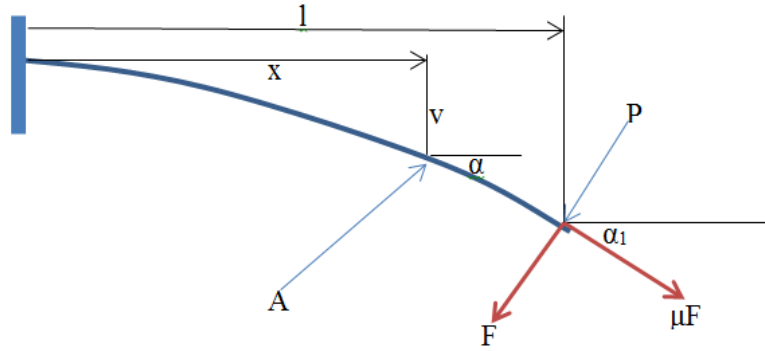


Figure 40 - Deflection of stripe

As shown in figure 8, point P is a point on the plastic stripe which is distance l away (horizontally) from the point of pivot. Similarly, A is distance x away. Suppose a tea shoot is in contact with the stripe at point P. The tangent to the stripe at A is inclined to the horizontal by an angle of α . At P, it is α_1 . The vertical deflection of A is v .

Take moments about A in clockwise direction. Ignore the moment created by the vertical distance.

$$M_A = (F \cos \alpha_1 + \mu F \sin \alpha_1)(l - x) \text{ -----(2)}$$

Equation of deflection of plastic stripe,

$$\frac{d\alpha}{dx} = \frac{d^2v}{dx^2} = \frac{M}{EI} \text{ --- (3)}$$

where M is the moment about a point distance x away from the pivot point and E is the elasticity modulus and I is the second moment of area of the cross section of the beam.

From (2) and (3),

$$\frac{d^2v}{dx^2} = (F \cos \alpha_1 + \mu F \sin \alpha_1)(l - x)$$

From this equation, it can be shown that,

V_P , vertical deflection at point P,

$$V_P = \frac{F}{3EI} [\cos(\alpha_1) + \mu \sin(\alpha_1)] l^3 \text{ -----(4)}$$

The goal is to maximise V_p . In order to do so, variation of V_p as α_1 varies should be examined. Let $T = [\cos(\alpha_1) + \mu \sin(\alpha_1)]$. Assume $\mu = 0.54$. Then,

$$T = [\cos(\alpha_1) + 0.54 * \sin(\alpha_1)]$$

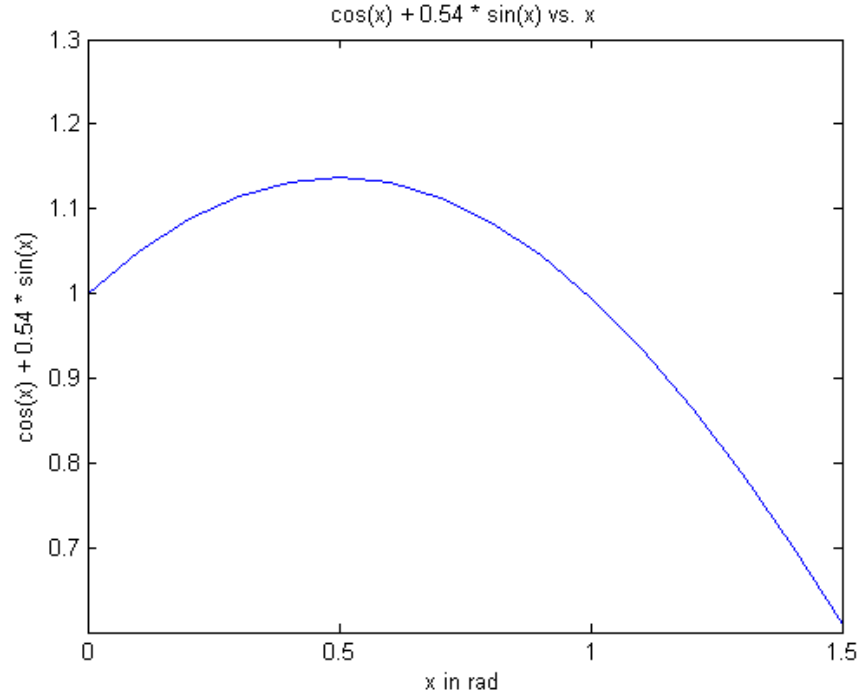


Figure 41 - T vs. α_1

According to Figure 40, T has a maximum. As a result, V_p will have a maximum with respect to α_1 . To maximise V_p ,

$$\frac{\partial V_p}{\partial \alpha_1} = 0$$

This results in $\tan \alpha_1 = \mu$

$$\alpha_1 = 28^\circ = 0.5 \text{ rad}$$

From the model for deflection of the plastic stripe,

$$F = -0.282 + 0.513 Y$$

$$\text{Therefore, } 3.058 * 10^3 EI = 0.513$$

$$EI = 1.68 * 10^{-4} \text{ kgm}^3 \text{s}^{-2}$$

$$\text{Therefore, } V_{p,\max} = 2.25 * 10^3 * F * l^3$$

The deflection of the stripe occurs due to the normal force acting on it, F.

$F = 2.008 + 0.11 x$, where x is the deflection.

Assume $x = 10\text{mm}$. Then $F = 0.03\text{ N}$

$$V_{p,\max} = 67.5 * l^3 \text{ -----(5)}$$

Where $V_{p,\max}$ is in meters.

From equation 3,

$$\frac{d\alpha}{dx} = \frac{M}{EI}$$

It can be shown that

$$\alpha_1 = \frac{F}{EI} (\cos\alpha_1 + \mu \sin\alpha_1) l^2/2$$

$\alpha_1 = 0.5\text{ rad}$. Therefore,

$$l = 70\text{ mm}$$

Then, $V_{p,\max} = 23\text{ mm}$

Finding coefficient of friction between the plastic stripe and tea shoots

Table 12 - Data for finding the coefficient of friction

weight (g)	h (mm)	l (mm)	tan (Θ)
26	84	177	0.54
38	81	177	0.51
51	90	177	0.59
56	81	177	0.51
59	81	177	0.51
66	85	177	0.55
75	83	177	0.53
Mean μ			0.54

Finding coefficient of friction between aluminium and tea shoots

Table 13 - Data for finding coefficient of friction

weight/g	l/mm	d/mm	tan(x)
31	176	158	0.49
39	176	162	0.42
45	176	160	0.46
53	176	159	0.47
65	176	158	0.49
mean COF			0.47

Design of the separators

Suppose the stripe is moving in a speed of U . Harvestable tea shoots are supposed to get in contact with the stripe and slide along it. Shorter arimbu are to go underneath it. The taller ones should bend and crawl under. Therefore, the dynamics of the stripe and tea shoot should be studied.

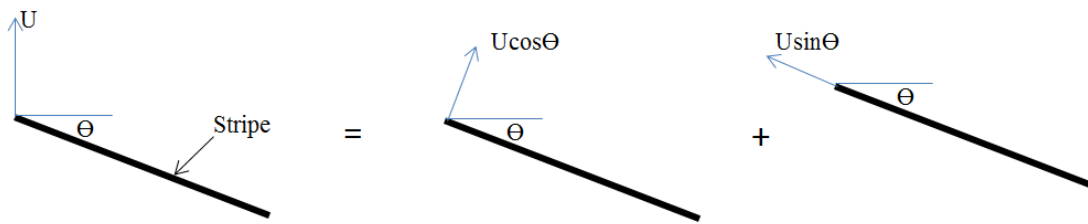


Figure 42 - Principle of superposition for the stripe

As shown in Figure 39, the speed of the stripe can be separated into its two component speeds. One component is along the stripe and the other is perpendicular to it. Take one harvestable tea shoot that interact with this stripe. Principle of superposition can only be applied to linear systems [41]. Effects on the systems due to motion in the X direction (refer figure 40) is linear. However that of Y direction is non-linear. Nevertheless, assume that it is linear. Therefore, it can be assumed that the principle of superposition can be applied to this system. Therefore, the effect on the tea shoot due to the initial speed U can be assumed to be equal to the sum of the two effects due to the component velocities. Hence, those two effects can be dealt separately and finally can be summed to obtain the total result.

Assume the shoot contacts the stripe at time $t=0$. As the stripe moves forward, the shoot slides and travels to the free end of the stripe. This happens because the shoot in

consideration is a harvestable one. A coordinate frame (X,Y) is defined taking the point of initial contact of the shoot as the origin. X is perpendicular to the stripe and Y is parallel (refer figure 33). Also, this coordinate frame is fixed on the earth.

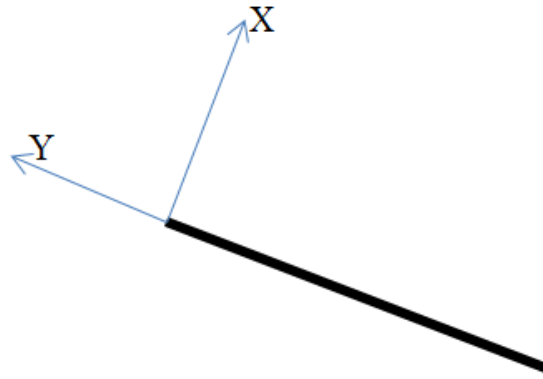


Figure 43 - Coordinate system

Motion in the X direction

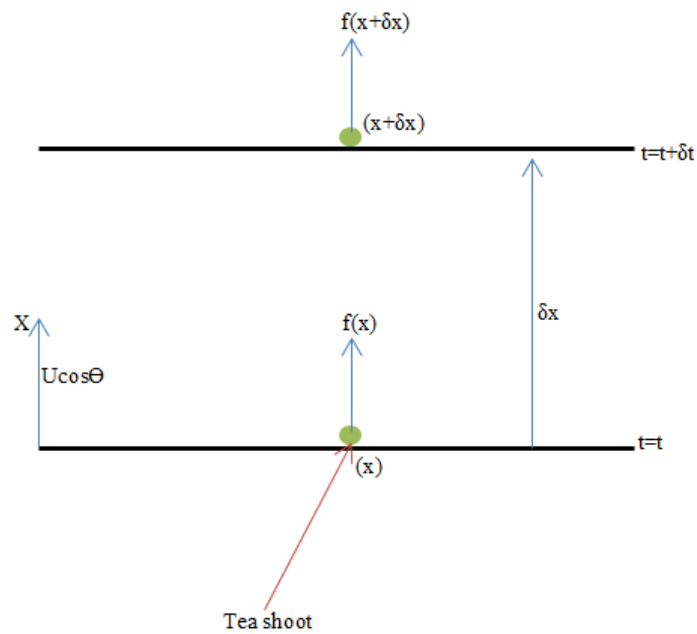


Figure 44 - motion in X direction

The stripe moves in X direction at a speed of $U\cos\Theta$. For clarity, X axis is illustrated vertically. As shown in Figure 44 - motion in X direction, at time $t=t$, tea shoot is in contact with the stripe. The force between the shoot and the stripe is $f(x)$. $f(x)$ is taken from the regression equation for deflection-force of harvestables. After a time period

(infinitesimal) δt , the stripe moves a distance of δx in X direction, deflecting the tea shoot. At that moment, the force becomes $f(x+\delta x)$.

At time t ,

$$x(t) = U t \cos \theta$$

Motion in Y direction

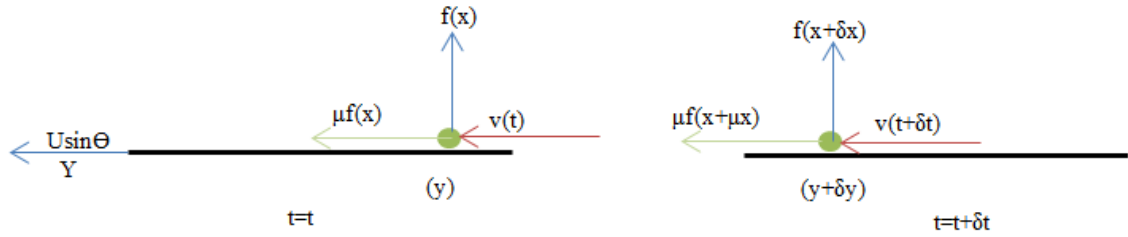


Figure 45 - Motion in Y direction

Y axis is drawn horizontally. The stripe moves in Y direction at a speed of $U \sin \theta$. At $t=t$, tea shoot moves at a speed of $v(t)$ in the Y direction relative to the earth. This becomes $v(t+\delta t)$ at $t=t+\delta t$. As the shoot touches the stripe and there exist a relative motion between the two bodies, a friction force acts between the shoot and the stripe. Furthermore, this friction force is due to the normal force $f(x)$ created due to the deflection of the shoot in the X direction. At $t=t$, the friction force is $\mu f(x)$ and it becomes $\mu f(x+\delta x)$ at time $t=t+\delta t$.

$$v(t) = \frac{dy(t)}{dt}$$

Applying $F=ma$ to the shoot (acceleration * mass = average force in the direction of acceleration)

$$\frac{dv(t)}{dt} = \frac{1}{2m} (\mu f(x) + \mu f(x + \delta x) - f(y) - f(y + \delta y))$$

$f(x)$ can be expressed as $k+cx$ at some constant height from the plucking table. Therefore,

$$\frac{dv(t)}{dt} = \frac{1}{m}(\mu(k + cx) - (k + cy))$$

Let L be the length of the stripe. Also suppose that the shoot traverses the stripe in the time period from t=0 to t=T.

Velocity of shoot relative to stripe in -Y direction = $U\sin\theta - v(t)$

Therefore,

$$L = \int_{t=0}^T (U\sin\theta - v(t))dt$$

$$L = UT\sin\theta - y(T) \text{----- (1)}$$

$$\frac{dv(t)}{dt} = \frac{1}{m}(\mu(k + cx) - (k + cy))$$

$$\frac{dv(t)}{dt} = \frac{1}{m}(\mu(k + cx) - (k + cy)) = \ddot{y}$$

Applying $x(t) = U\cos\theta$,

$$\ddot{y} = \frac{k}{m}(\mu - 1) + \frac{\mu c U \cos\theta}{m}t - \frac{c}{m}y$$

Applying Laplace transformation and initial conditions $y(0) = 0$ and $\dot{y}(0) = 0$

Let

$$\frac{k}{m}(\mu - 1) = a$$

$$\frac{\mu c U \cos\theta}{m} = b$$

$$\frac{c}{m} = d$$

Therefore,

$$Y(S) = \frac{aS^2 + b}{S^2(S^2 + d)} \text{ in Laplace domain}$$

$$Y(S) = \frac{a}{S^2 + d} + \frac{b}{S^2(S^2 + d)}$$

$$y(t) = \left(\frac{a}{d^{\frac{1}{2}}} - \frac{b}{d^{\frac{3}{2}}} \right) \sin(\sqrt{d} t) + \frac{b}{d} t$$

Substitute into equation 1

$$L = UT \sin \theta - y(T) \text{ ----- (2)}$$

And

$$x(T) = UT \cos \theta \text{ ----- (3)}$$

There is some $x(T)$, that is the deflection of the shoot in X direction which can be used to categorise harvestables and arimbus. Using this value of $x(T)$ and equation 3, respective value of T can be found. Subsequent substitution of that T value into the equation 2 will give the appropriate θ value. In order to do so, the value of L has to be fixed.

The force required to bend a harvestable tea shoot is given by the equation

$$F_h = 4.74 + 0.117 x - 0.0257 h$$

$h = 74\text{mm}$ (the selection is done at this height)

This F_h is given as grams. In order to convert it to Newton, F_h should be multiplied by 9.81×10^{-3}

Therefore,

$$F_h = 0.028 + 1.15X$$

Where X is in N/m.

Therefore,

$$k = 0.028$$

$$c = 1.15$$

After weighing a tea shoot it was found that the weight is approximately 3g. Therefore

$$m = 3 * 10^{-3}$$

From previous experiments, it was found that $\mu = 0.47$

Therefore,

$$a = -4.947$$

Assume $U = 0.5 \text{ m/s}$

$$b = 90.1 \cos\theta$$

$$d = 383.33$$

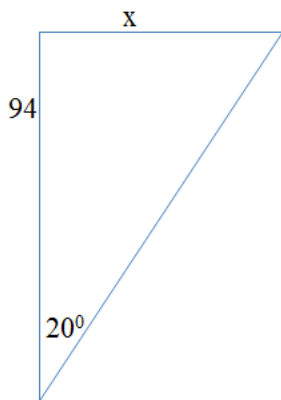
$$y(t) = -(0.253 + 0.012\cos\theta) \sin(19.58t) + 0.235t\cos\theta$$

Let $L = 50 \text{ mm}$

Therefore, equation 2 becomes

$$5 = 50T\sin\theta + (25.3 + 1.2\cos\theta) \sin(19.58T) - 23.5T\cos\theta \text{ ----- (4)}$$

Assume that tea shoots deflect, keeping their centre of rotation 20 mm beneath plucking table. Assume maximum allowable deflection angle of harvestables is 20° . Hence, the height from centre of rotation to the position of selection is $20 + 74 = 94 \text{ mm}$



$$x = 34 \text{ mm}$$

From equation 3,

$$T = \frac{0.068}{\cos\theta}$$

Substitute this into equation 4.

Figure 46 - Deflection angle

$$3.4\tan\theta + (25.3 + 1.2\cos\theta) \sin\left(\frac{1.331}{\cos\theta}\right) - 6.598 = 0$$

Solving this equation for Θ using MATLAB,

$$\Theta = 65^0$$

Testing of prototype 2

K = Number of harvestables in the area of interest

A = number of arimbus in the area of interest

Subject 1

A = 5 , H = 4

deflection of the stripe (mm)	a	h	Selectivity
5	5	3	5.62
20	2	3	22.39
25	0	0	10.00

Subject 2

A = 5 , H = 2

deflection of the stripe (mm)	a	h	Selectivity
5	5	2	10.00
20	3	2	25.12
25	0	0	10.00

Subject 3

A = 6 , H = 3

deflection of the stripe (mm)	a	k	Selectivity
5	5	3	14.68
20	2	2	21.54
25	0	0	10.00

Mean of the three subjects

deflection of the stripe (mm)	Selectivity
5	10.10
20	23.02
25	10.00

Testing of prototype 3

Subject 1

deflection of the stripe (mm)	a	h	Selectivity
5	3	4	31.62
20	1	3	38.31
25	1	0	6.81

Subject 2

deflection of the stripe (mm)	a	h	Selectivity
5	3	2	25.12
20	2	2	39.81
25	0	1	31.62

Subject 3

deflection of the stripe (mm)	a	h	Selectivity
5	3	3	31.62
20	2	2	21.54
25	0	0	10.00

Mean of the three subjects

deflection of the stripe (mm)	Selectivity
5	29.45
20	33.22
25	16.14

APPENDIX B

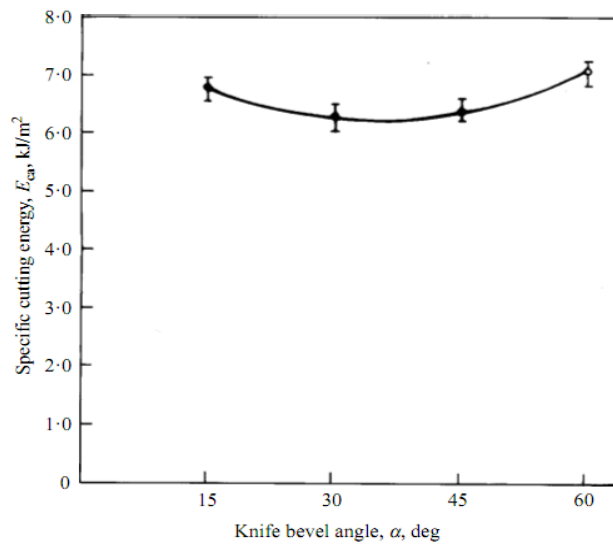


Figure 47 : Variation of specific cutting energy with bevel angle (source: [4])

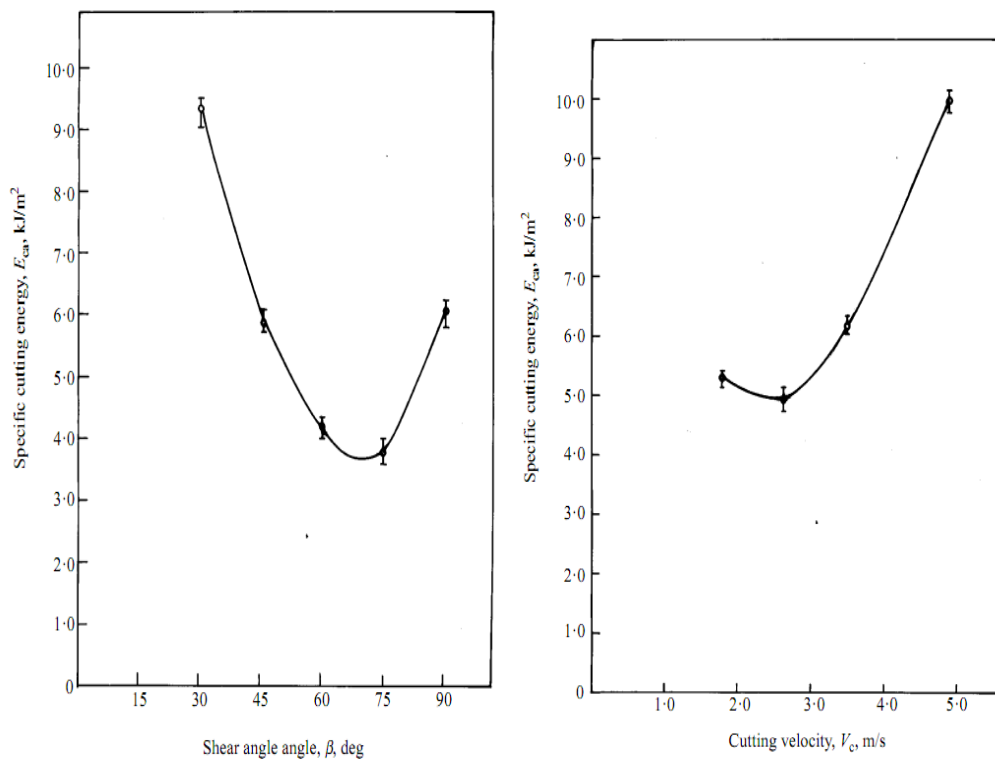


Figure 48 : variation of specific cutting energy with shear angle and cutting velocity (source: [6])

APPENDIX C

Table 14 : Changes in green leaf biochemical constituents due to machine plucking (source: [8])

Parameter	Hand Plucked	Shear Plucked-A	Shear Plucked-B
Total catechins (%)	18.4	17.8	18.2
Total polyphenols (%)	27.7	26.6	27.5
Carotenoids (mg/100g)	71.0	66.0	69.1
Chlorophyll a (mg/100g)	1091	1201	1137
Chlorophyll b (mg/100g)	448	493	482
Lox activity (U/mg protein)	11.5	14.0	12.9
PPO activity (U/mg protein)	24.4	23.1	23.0
Total lipid (%)	6.3	7.7	7.3
Total protein (%)	14.1	15.3	15.1

Table 15 : Effect of tea plucking method on made tae yield (kg per ha) of China Seedling tea (source: [11])

Treatment	2000/1	2001/2	2002/3	2003/4	2004/5
Plucking method					
Hand	3090	2195	1912	2394	2566
machine	3687	2288	1868	2203	2501
Mean	3389	2242	1890	2299	2534

Table 16 : Effect of tea plucking method on made tae yield (kg per ha) of PC 108 (source: [11])

Treatment	1999/0	2000/1	2001/2	2002/3	2003/4	2004/5
Plucking method						
Hand	5364	7026	4434	9409	9045	8379
machine	5044	6438	3785	7390	6472	4876
Mean	5204	6732	4110	8400	7759	6628

APPENDIX D

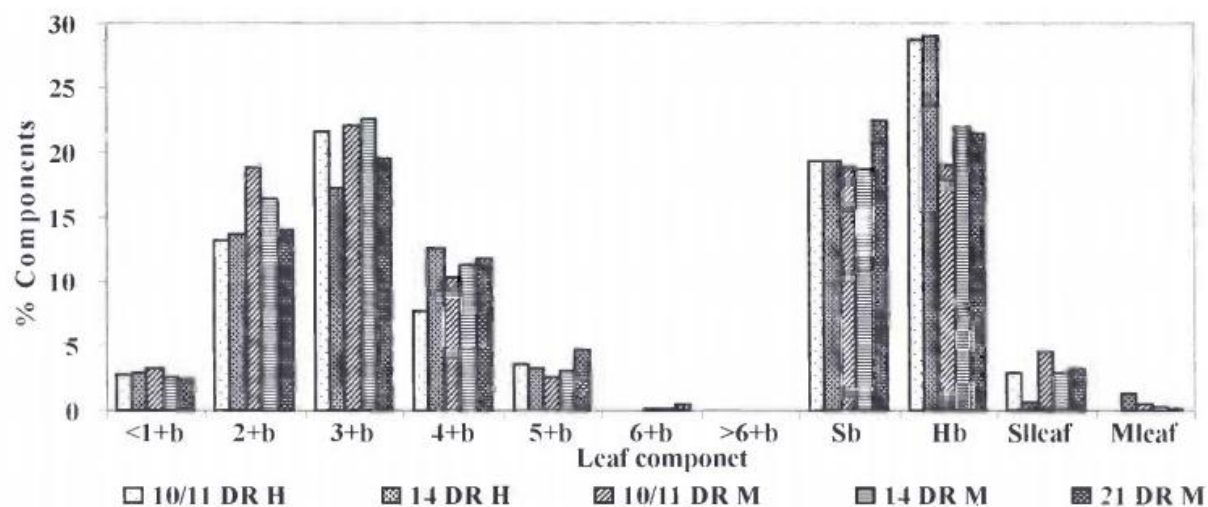


Figure 49: Present components by weight of green leaf of PC 108(source: [11])

1+b, 2+b, 3+b, 4+b, 5+b, 6+b = shoots of one leaf and a terminal buds, two leaves and a terminal bud, three leaves and a terminal bud, four leaves and a terminal bud, five leaves and a terminal bud, six leaves and a terminal bud, Sb = Soft banhji, Hb = hard banhji, S leaf = Soft leaf, M leaf = Maintenance/coarse leaf; H – Hand plucking, M – Mechanical plucking, DR – Days per Round

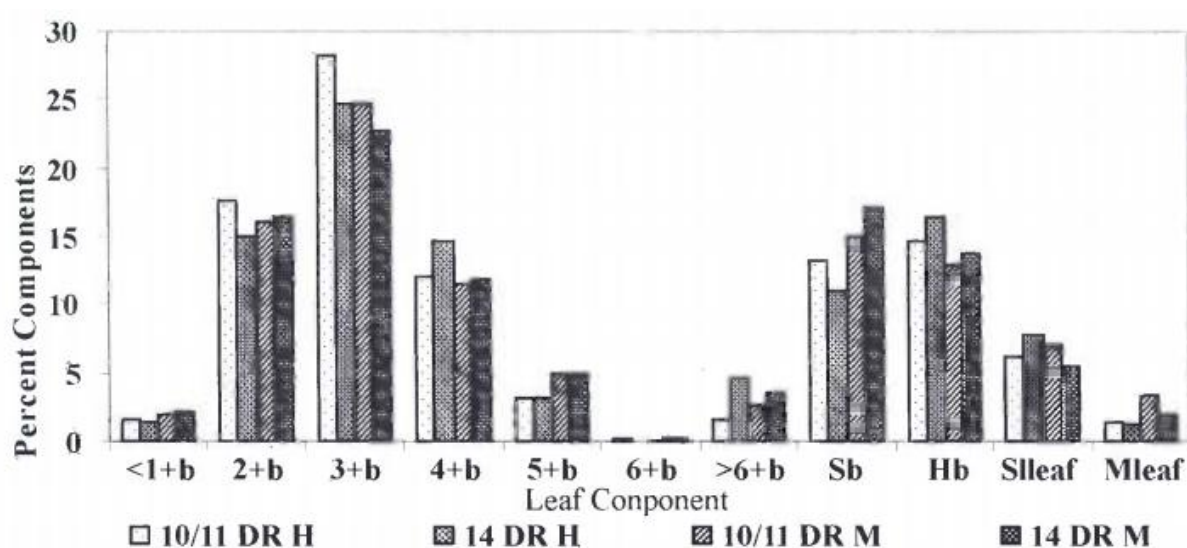


Figure 50 - Present components by weight of green leaf of China seedling tea (source: [11])

1+b, 2+b, 3+b, 4+b, 5+b, 6+b = shoots of one leaf and a terminal buds, two leaves and a terminal bud, three leaves and a terminal bud, four leaves and a terminal bud, five leaves and a terminal bud, six leaves and a terminal bud, Sb = Soft banhji, Hb = hard banhji, S leaf = Soft leaf, M leaf = Maintenance/coarse leaf; H – Hand plucking, M – Mechanical plucking, DR – Days per Plucking round.