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Performance Evaluation of a Variable Pitch Potato Grader

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Abstract

Manual grading of potatoes in Kenya has resulted in inconsistencies, quality variations and financial losses to small-scale farmers due to low market prices for poorly classified produce. To mitigate these challenges, this study aimed at developing and evaluating the performance of a potato grading machine to enhance uniformity and overall quality of potato tubers. The research involved determining the engineering properties of Shangi potato variety and developing potato grader machine. The designed grader consisted of a feeding hopper, conveyor belt, grading unit, and collection trays. Grading capacity, grading efficiency, and mechanical damage index were assessed by varying grading unit speeds, angles of inclination and feed rates. The results showed that the grading capacity increased with higher grading unit speeds, inclination angles, and feed rates. The optimal operating conditions were observed at a grading unit speed of 4 rpm, an inclination angle of 0 degrees and a feed rate of 3400 kg/hr. The prototype potato grader achieved a grading capacity of 3968 kg/hr, with an efficiency of 89.34% and a mechanical damage index of 2.94%. The results demonstrate that the potato grading machine effectively enhances grading efficiency while minimizing mechanical damage. This grading machine offers a practical and sustainable solution for small-scale farmers to produce high-quality graded potatoes in line with market demands. It is recommended that future research may include further optimization by exploring various grading unit speeds, feed rates, and inclination angles. Implementing padding on the collection trays could further reduce mechanical damage to the graded tubers. Furthermore, investigating alternative power sources may enhance the grader's versatility and extending testing to fruits and other tubers would broaden its applicability in the agricultural industry.

Keywords: Grading, Potato tubers, machine, development, performance, evaluation

INTRODUCTION

Potato (Solanum tuberosum) is the world's top non-grain food commodity. Potato produces more food per unit area than any other major food crops. It is the world's most important tuber crop ranking first in volume produced among root and tuber crops grown in more than 125 countries. It is consumed almost daily by more than a billion people (Gebru *et al*., 2017). Global production of potato over the last two decades, expanded from 267 to 375 million tons (Djaman *et al*., 2021). The cultivation of potatoes in Africa was initially initiated by European settlers during the late 1800s. However, it was not until the mid-1950s that the practice of potato farming became more widespread among African populations. Subsequently, the tuber has experienced significant growth, resulting in a production of over 25 million metric tons in Africa for the year 2017 (International Potato Center, 2019).

Potato production and consumption in Kenya has witnessed a notable increase, positioning the crop as the second most consumed after maize (Janssens *et al*., 2013; Muthoni *et al*., 2010; Taiy *et al*., 2016). This increase in potato cultivation is mostly attributed to the efforts of over 800,000 small-scale farmers who engage in its cultivation. Moreover, the potato value chain has emerged as a significant source of employment, estimated to provide livelihoods for approximately 2.5 million people (Mutinda *et al*., 2021; Amwine, 2020; International Potato Center 2019; Kaguongo *et al*., 2015).

There are 19 adapted potato varieties in Kenya (NPCK 2017) with Shangi variety being the most common and highly consumed variety due to its early maturity and high productivity although the number of varieties has increased beyond 50 with the introduction of new ones from other countries such as Netherlands and Germany (Moletsane *et al*., 2021). Most of the potatoes produced in Kenya are sold locally on the market as fresh produce and are subsequently processed into different foodstuff either at the household or at industrial level (Musita *et al*., 2019; Consolata, 2018). Furthermore, processed potato products such as crisps and French fries (locally known as chips) are on high demand among urban consumers, hence are a great part of menus in restaurants and hotels in major urban centers (Muthee *et al*., 2021). This, therefore, makes the potato a major part of the diet of many Kenyan consumers.

Potato cultivar plays an important role in improving food security and cash income of smallholder potato growers due to its high yield potential per hectare and nutritious tuber (Wijesinha-Bettoni & Mouillé, 2019). The Kenyan Government has recognized the critical role potatoes play in alleviating food shortages given that potato provides higher yields compared to maize and is less affected by climate change (Sigrid *et al*., 2016). The issue of food loss is a highly important factor in securing the stable production required to combat hunger and raise incomes. Once harvested, potatoes can be used for a variety of purposes as a fresh vegetable for cooking at home, as raw material for processing into food products, food ingredients, starch and alcohol production, as feed for animals, and as seed tubers for growing in the next season (López-Córdoba *et al*., 2019).

Around the world, consumers demand is shifting from fresh tubers to processed products and ever greater quantities of potatoes are being processed to meet rising demand for convenience food and snacks (Iese *et al*., 2018). As a result, a group of unit operations like washing, drying, grading, waxing, packaging and pre-cooling are performed after harvesting and before they reach the ultimate consumers. In this group of unit operations, grading is one of the most important operations which add value to the product and gives higher economic gain to the producers (Iese *et al*., 2018). Grading of vegetables on the basis of size and shape is important for marketing uniform high quality produce (Bhargava & Bansal, 2021). Size variations in vegetables like potatoes provide a base for grading them into different categories. Consumers prefer potato tubers with equal weight and uniform shape. Mass grading of vegetables can reduce packaging and transportation costs, and also may provide an optimum packaging configuration. Grading of potatoes has been proposed as a step to improve the overall quality of potatoes delivered to packing companies and to reduce on-farm storage space requirements (Su *et al*., 2018).

In Kenya, the process of grading predominantly involves manual efforts by farmers, wholesalers, retailers, and even consumers. This method demands substantial labor and extended working hours. However, the manual grading of potato tubers tends to lack uniformity due to differing quality assessments among individuals. This variability leads to the likelihood of human-related mistakes and inconsistencies, as highlighted in previous studies (Alemu, 2019; Patel *et al*., 2015). Furthermore, manual grading is costly, time-consuming and inefficient. Due to various reasons stated above, most farmers market their products without grading and obtain very low price. Above all, the new marketing trends, adopted by World Trade Organization (WTO), demand high quality graded products (Margulis, 2018).

In order to sell potato to processors, and join the regional and international markets as exporters, small and medium-scale farmers need to produce a high quality, standardized product. Potato grading machines suitable for use on small-scale farms will help farmers respond to the new and emerging marketing opportunities positively through provision of high quality and standardized tubers suitable for the potato processing industry (Alemu Anawte, 2019). This study aimed at determining some engineering properties of shangi potato variety grown in Uasin Gishu County and evaluating the performance of the prototype potato grading machine.

MATERIALS AND METHODS

This study examined the physical characteristics of the Shangi potato variety, which is one of the most commonly grown varieties in Uasin Gishu, Kenya (NPCK 2019). Three 50kg bags collected from three different farms with good potato production practices were mixed thoroughly and put in 10 batch boxes. The tubers in each of the boxes weighed approximately 15kg. Five alternating boxes were selected and the mass, major, intermediate and minor diameters were taken and recorded. The percentage of each range was calculated from each batch and an average taken. A vernier caliper was used to measure three perpendicular axes for each tuber with 0.1mm accuracy. The weight of each tuber was measured on an electric balance to 0.01g. The mean, standard deviation maximum, minimum, coefficient of variation for each perpendicular axis and mass were calculated using Microsoft excel 2013.

Table 1: The size range of potatoes and its associated common use

Item	category	Size Range (mm)	Common use
1	Charts	< 28	Animal feed
2	Small size	35 - 50	Seed, mashing, wedges
3	medium	50 - 80	Mashing, Stews
4	Large	>80	*Crisping, chips*

Source: (NPCK 2019)

Frictional Properties of Potato Tubers

The frictional properties under study included coefficient of static friction, coefficient of dynamic friction and angle of repose.

Coefficient of static friction was determined for surfaces used in the construction of the potato grader, sheet metal and rubber. An open box was filled with 10 kg of potatoes and placed on the test surface then it was lifted on one side until just when the box started sliding and the angle was recorded. The process was replicated three times using different samples of potatoes an average was then determined using.

$$\mu_s = \tan \alpha$$

(Equation 1)

Whereas, the coefficient of dynamic friction was obtained using a topless and bottomless plywood box with dimensions 300*300*200mm. The box was placed on the test surface and filled with 10kg quantity of potato tubers, a horizontal force was applied on the plywood box until it moved uniformly. The test was replicated three times and average obtained. The coefficient was then determined using equation 2 (Amin *et al*., 2004).

$$\mu_d = \frac{F}{mg}$$

(Equation 2)

A bottomless cylinder filled with potato tubers was placed on the test surface and then raised carefully allowing the tubers to flow down and form a natural slope. The diameter and height of the formed slope was measured and eq 2 used to determine the angle of repose.

$$\imath^{1}\left(\frac{height\ of\ ile}{base\ length\ of\ ile\!\left/_{2}\right.}\right)$$

(Equation 3)

Development of the Potato Grader

The component parts of the prototype potato grader included feeding tray hoppers, feeding unit, grading unit, collection trays, pulleys, drive belts, drive chains and sprockets, power source, and chassis.

Functional Design of the Grading Unit

The grading unit was of conveyor type with 64 cylindrical tubes of 25mm equally spaced. The conveyor grading unit consisted of 32 sections of two tubes. One was fixed to the conveyor chain and the other ran on tracks which were sloped to create a variable gap from 0-80mm. Below the conveyor grading unit were three chutes to collect the graded tubers with ranges from <35mm, 35-40 mm, and 50-80mm. The fourth chute collected potatoes that had a minor diameter greater than 80mm and was mounted at the end of the conveyor grading unit.

The grading machine was designed to operate on the principles of a rotating grading unit with a variable gap from 0-80mm. The feeding unit was placed such that it fed the tubers onto a hopper on the grading unit. The grading unit was designed to create a variable gap that allowed the tubers to drop when the tuber diameter was equal to the size of the gap. The grader was designed to grade the potatoes by their minor diameters. This was achieved by rotating and rolling the tubers between the fixed tube and the non-fixed tube, which ran on a sloped track that created the variable gap. Those potatoes that were greater than 80mm would not drop and were carried to the fourth chute mounted at the end of the conveyor grading unit. The output speed of the electric motor with 1.5hp and maximum speed of 1500 rpm was reduced using a reduction gearbox with a ratio of 1:20, and the various test speeds were attained by changing the driven pulleys with 100mm, 200mm, and 300mm diameters.

Feeding Hopper

This hopper was designed to deliver potato tubes to the feeding conveyor. Using sheet metal of 1.5mm thickness. The hopper was mounted at 300 angle which is greater than the repose angle of Shangi variety of potatoes on sheet metal.

Feeding Conveyor

This section was designed to have a rubber conveyor belt mounted on two cylindrical pulleys with wall on each side of the conveyor to prevent the tubers from falling. The conveyor unit was driven with an electric motor of 0.5hp and maximum speed of 1500rpm. The speed was reduced using a reduction gearbox with a speed ratio of 1:20 and to attain different feed rates of 3400kg.hr-1, 4000kg.hr-1 and 4600kg.hr-1 using 200mm, 150mm and 100mm diameter pulleys respectively. The drive pulley on the gear box had a 100mm diameter. The speeds were used to test performance of the machine on grading of the tubers.

Frame

The frame supports the entire weight of the grading machine. This weight include; weight of the grading unit, feed hopper, pulleys motor drive chains, gear box and potato. The machine was designed in two sections. The weight of the conveyor section includes; the weight of the conveyor, pulleys, conveyor rubber belt, electric motor with reduction gear box and feeding hopper.

Receiving Trays

Beneath each grading unit, there is a tray padded with cushioning material to catch the tubers at each size grade section. The tray has four sections along the length of the grading unit to collect the graded tubers.

Design of the Potato Grader Apertures

The grading pitch width of the separation points between tubers sizes was suggested by (Peleg, 1985) and is given by equation 4

$$X_{12} = \left[\frac{\mu_2\sigma_1^2 - \mu_1\sigma_2^2}{\sigma_1^2 - \sigma_2^2}\right] \pm \left[\left(\frac{\mu_2\sigma_1^2 - \mu_1\sigma_2^2}{\sigma_1^2 - \sigma_2^2}\right)^2 - \frac{\mu_2^2\sigma_1^2 - \mu_1^2\sigma_2^2 - 2\sigma_1^2\sigma_2^2\, ln\left(\frac{\sigma_1}{\sigma_2}\right)}{\sigma_1^2 - \sigma_2^2}\right]^{1/2}$$

(Equation 4)

Where; X12 is the grading pitch of the diameter of separation point between potato tuber sizes 1 and 2, µ1 and µ2 are the mean geometric diameters of potato tuber sizes 1 and 2. Also, σ1 and σ2 are the standard deviation of the mean geometric diameters of the potato tuber sizes. The equation 3 in conjunction with results from objective one; physical properties of potato tubers, the various pitch sizes for attaining the NPCK 2019 recommended size categories of potato tubers was used and the results recorded

Performance Evaluation of the Prototype Potato Grading Machine.

The performance of the prototype potato tuber grader was evaluated based Grading capacity, grading efficiency and mechanical damage.

Potato Tubers

Three 50kg bags collected from three different farms within Uasin Gishu County, Ainabkoi Sub County that have good potato production practices. The sample was mixed thoroughly and put in 10 batch boxes. The tubers in each of the boxes weighed approximately 15kg. 5 alternating boxes were selected and the mass, major, intermediate and minor diameters were taken and recorded. The mass of each category was recorded from each batch and an average taken. A vernier caliper was used to measure three perpendicular axes for each tuber with 0.01mm accuracy. The weight of each tuber was measured on an electric balance to 0.01g. In order to determine the physical attributes of potato tubers, the sample, free from any injuries, were kept in a refrigerator at a temperature of 4 0C and relative humidity of 95% for 24 hours as recommended by Hurst (1993) to offset the effect of the environment.

Those with damages such as bruises, abrasions decay and greening were not included in the sample. Based on measurements made potato tubers were graded into specific ranges based on the higher dimensions. The ranges are <35mm, 35-50mm, 50-80mm and >80mm. each category was then colour coded for ease of identification during grading. After each treatment the weight of tubers collected from each tray was weighed and recorded, the time it took to grade the samples and the weight of damaged potatoes was also noted

Experimental Design.

The experiment was laid in a split-split plot design having grading unit speeds as the main plots, the angle of inclination as sub-plots and feeding rates as sub-sub plots with three replications as a block. The design was 33 factional combinations with three replicates giving 81 total experimental (3*3*3*3). The treatments were three levels of grading unit speeds of (6, 4 and 2 rpms), three levels of angle of inclination (-15o ,0o and 15o) and 3 levels of feeding rates of 3400kghr-1, 4000 kghr-1 and 4600 kghr-1 .

The independent variables are speed of grading unit (6, 4 and 2 rpm) inclination of the grading unit (-50, 00 and 150)) and feed rates (3400, 4000 and 4600kghr). The different grading speed and the feed rates were achieved by changing pulleys with different diameters from 100mm to 300 mm.

The weight of tubers on each tray was recorded after each treatment and replication was done, the weight of damaged tubers was also recorded.

Grading capacity (kghr-1)

This was determined based on the amount of the potato tubers graded within a specified period.

$$Grading\ Capacity\ (kg.hr^{1}) = \frac{Weight\ of\ graded\ tubers\ (kg)}{Total\ time\ taken\ to\ grade\ (hr)}$$

(Equation 5)

Grading System Efficiency (%)

The grading efficiency was determined by comparing observed weight and the expected weight of the potato tubers in each tray and efficiency calculated using the root mean square error method.

$$RMSE = 100 * \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2}$$

(Equation 6)

Where; X_I is the expected weight, M is the observed weight and n is the number of observations. RMSE indicates the level of scatter in a model, providing a term by term comparison of the actual deviation between the predicted and observed values. Lower RMSE values reflect a better model in terms of its absolute deviation (Brkic *et al*, 2019).

Damage Index (%)

This was estimated by the fraction of the total weight of damaged potatoes verse the weight of the potatoes in the tray.

$$Damaged\ Index, DI(\%) = \left(\frac{Total\ no.of\ tubers\ with\ abrasion}{Total\ no.of\ tubers\ in\ \mathrm{sample}}\right).100$$

(Equation 7).

RESULTS AND DISCUSSION

Physical properties

The physical properties of the potato tubers were determined by measuring the major, intermediate, and minor diameters using a Vernier caliper with an accuracy of 0.01mm and weight measured using a digital scale with accuracy of 0.01 g. the maximum and minimum major intermediate and minor diameters and mass were recorded as shown in Table 2.

Table 2: Physical properties of Shangi potato tubers

Property	Mean	Min	Max
Major Diameter (mm)	53.913	27.000	111.000
Inter Diameter (mm)	43.362	24.000	73.000
Minor Diameter (mm)	36.620	21.000	59.000
Mass (Grams)	55.877	12.000	387.000
Mean Geometric Diameter (mm)	43.934	25.275	74.506
Surface Area (mm2)	6250	2010	1.74E+04
Volume (mm3)	4.86E+04	8450	2.16E+05
Sphericity	0.825	0.591	1.000
Density (Kg/M3)	1.168	0.400	*5.478*

Mechanical Properties

The angle of repose ranged from 21.530 and 29.720 on sheet metal and 22.640 to 31.230 on rubber surface. The maximum and minimum angle of repose was recorded as 21.530 and 31.230 on sheet metal and rubber surfaces respectively.

The static coefficient of friction ranged from 0.21 to 0.28 on sheet metal and from 0.25 to 0.39 on the rubber surface. The maximum and minimum static coefficient of friction were as 0.21 and 0.39 on sheet metal and rubber surfaces respectively.

The dynamic coefficient of friction ranged from 0.39 to 0.58 on sheet metal and from 0.61 0.68 on rubber. The minimum and maximum coefficient was recorded on sheet metal 0.39 and 0.68 for rubber surfaces.

Developed Grading Unit

Calculated grading unit apertures are as presented in Table 3.

Table 3: Grading unit openings

NPCK Recommended Potato Tuber Sizes (mm)	Calculated Variable gap opening (mm)
<35mm	0-23.28
35-50	23.28-33.95
50-80	33.95-55.14
>80	>55.14

Using the above data the prototype potato grader was developed

Performance of the Potato Grader

In order to select the appropriate operational parameters for the grading process, it was necessary to determine the grading capacity, grading efficiency and mechanical damage index of the tubers. This parameter varied with feeding rates, angle of inclination of the grading unit and the speeds of the grading unit. It was noted therefore that the quality of the graded tubers was mainly dependent on the performance of the potato grader as shown in Table 3.

Table 4: Interaction effect of grading unit speeds, angle of inclination and feed rate on grading capacity, grading efficiency and mechanical damage index.

Speed (RPM)	**Angle (Ø)**	**Feed Rate (Kg/Hr)**								
		3400			**4000**			**4600**		
		GC	**GE**	**MD**	**GC**	**GE**	**MD**	**GC**	**GE**	**MD**
6	-15	3218.67	89.72	3.22	3752.42	90.33	3.15	4216.00	90.60	3.53
	0	3230.00	88.13	4.60	3764.90	89.56	3.07	4417.50	89.94	3.62
	15	3230.00	89.75	3.91	3668.82	90.14	3.92	4154.00	89.80	5.37
4	-15	3128.00	93.34	3.02	3529.04	93.03	3.54	3968.00	93.18	4.72
	0	3111.00	90.57	2.65	3423.88	91.38	3.07	4030.00	90.27	3.50
	15	2946.67	86.97	2.26	3367.56	87.19	2.22	4115.25	89.11	2.75
2	-15	2810.67	86.82	2.05	3302.50	87.25	2.38	3699.33	87.66	2.47
	0	2788.00	90.81	2.88	3346.89	88.22	3.29	3875.00	86.76	3.82
	15	2825.78	87.95	1.86	3408.93	84.43	1.94	3668.33	85.57	2.57
	Total	27288.79	804.06	26.45	31564.94	801.53	26.58	36143.42	802.89	32.35
	Average	3032.09	89.34	2.94	3507.22	89.06	2.95	4015.94	89.21	3.59
	Std.Dev	189.42	2.10	0.89	179.18	2.58	0.65	243.32	2.27	0.97

Grading Capacity, (Kg/hr)

The statistical analysis and ANOVA clearly indicated that the grading unit speeds and feeding rate during the grading process showed that there was significant influence at ($p<0.05$) on the grading capacity. However, the angle of inclination had little influence. The figure 1 shows the combined effect of grading unit speeds and feed rate on grading capacity of the proto type potato grader.

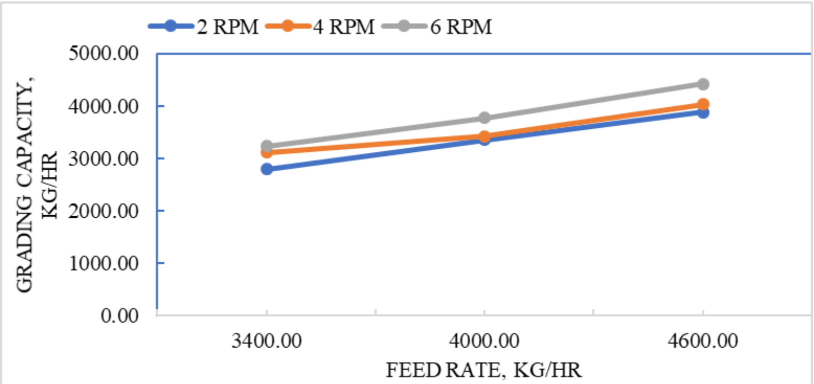

Figure 1: Effect of grading unit speeds and feed rate on grading capacity of the proto type potato grader.

A maximum grading capacity of 4417.50 Kghr-1 was achieved when the feed rate was 4600kghr-1, angle of inclination 00 and grading unit speeds of 6 rpm. Ghanbarian and Kolchin (2008) noted that, on the basis of a feeding rate of 2,500 kg/h and the national production average of 22,000 kg/ha, their machine could grade potato tubers from 1 ha in 8.8 h. Further, an experienced human grader can sort 125 kg/h, and it would therefore need a minimum of 20 people to sort the same mass of potatoes in the same time.

It was also noted that the grading capacity increased with the increment of both feed rate and grading unit speeds. This is also shown by the regression equation:

Grading Efficiency, %

The statistical analysis, ANOVA showed that the feeding rate, grading unit speeds and angle of inclination had significant influence ($P<0.05$) on the grading efficiency. The figure 4.3 shows the combined effect of grading unit speeds and angle of inclination on grading capacity of the proto type potato grader.

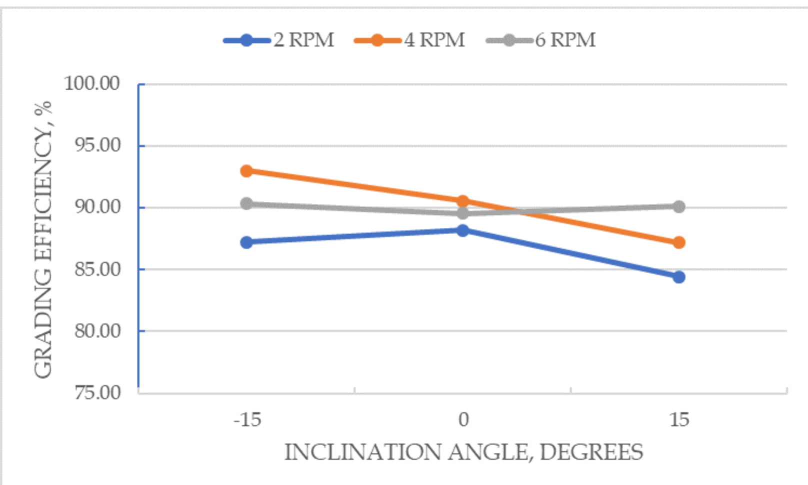

Figure 2: Effect of grading unit speeds and angle of inclination on grading efficiency of the proto type potato grader.

Highest efficiency was observed at 93.34%and 93.18% when the grader was at a feeding rate of 3400 and 4600 kghr-1, angle of -150 and grading speed of 4 rpm. The results are in line with studies carried out by Xing *et al*., (2021) where, using a conveyor grader for grading potato variety when operated at a feed rate and conveyor chain speed of 3.52 kg/s and 1.24 m/s respectively, showed that grading accuracy values ranged from 85.96 to 90.35, with a mean of 88.07. The results of this study also aligned with the findings of the study conducted by Alemu *et al*., (2021), which examined the functionality of a potato grader and documented a highest efficiency rate of 97.67% for its grading system.

Conversely, the lowest grading efficiency was noted when the grading unit speed was at 2 rpm, angle of inclination 150 and feed rate of 4600kg.hr-1, this could have been caused by piling up of the tubers at the inlet of the grading unit, this made it difficult for the potatoes to drop through the gaps during the grading process.

Mechanical Damage Index

The statistical analysis on mechanical damage on the potato tubers during grading indicated that the feed rate and grading unit speeds had significant effect ($P<0.05$) on the level of tuber damage. The angle of inclination had no significant influence. The figure 4.4 shows the combined effect of grading unit speeds and feed rate on mechanical damage of the proto type potato grader.

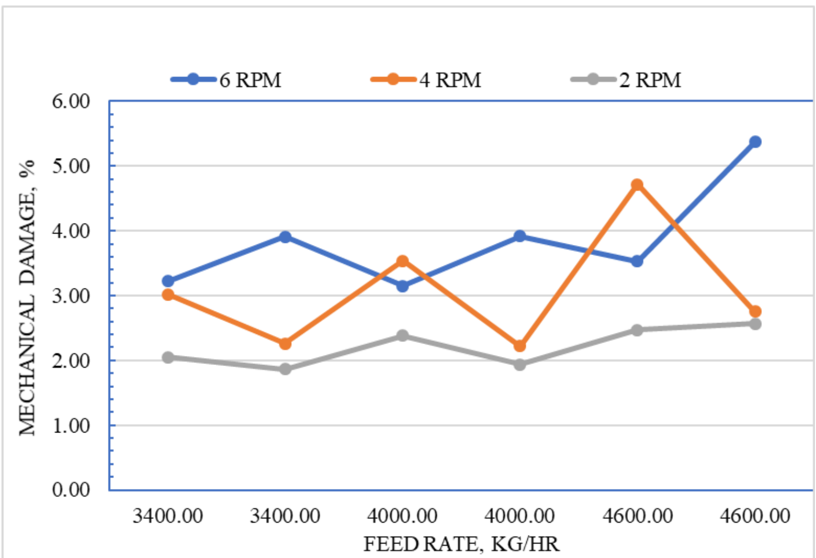

Figure 3: Effect of grading unit speeds and feed rate on grading capacity of the proto type potato grader.

The lowest damage is observed at 1.86%, when the grader was set at 3400kghr-1 feed rate and angle of inclination of 150 and grading unit speed of 2 rpm and the greatest damage of 5.37% was witnessed when the grader was operated at a feed rate of 4600 kg.hr-1,150 angle of inclination and speed of 6 rpm. Therefore, it is evident that increased throughput and higher machine operating parameters amplified mechanical damage because of greater friction and knocking between the tubers and on the machine surfaces.

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CONCLUSION AND RECOMMENDATIONS

Conclusion

The developed prototype potato grader effectively sorted the potatoes in accordance with the national standards outlined by NPCK. The newly designed variable pitch potato grader demonstrated efficiency and suitability for potato grading tasks at a rate of 3182 kg/hr with a commendable 93% effectiveness. Physical characteristics of shangi potato variety in this study were mass ranging from 12 to 387 grams, mean geometric diameter of between 25.23 and 74.5 mm, averages of minor, intermediate and major diameters of 36.62, 43.36 and 53.91 mm respectively. Mechanical properties presented ranges for metal and rubber surfaces of 21.530 and 31.230 for repose angle, 0.21 to 0.39 and 0.39 to 0.68 for static and dynamic coefficients of friction respectively.

Potato grader was developed with the following components; feeding hopper, feeding conveyor unit, grading unit, collection trays, pulleys, drive belts, drive chains, sprockets, power source and chassis to classify potatoes in the following categories <35mm, 35-50 mm, 50-80mm and >80mm as per NPCK standard requirements

The variable pitch potato grader developed was efficient and is appropriate for grading potatoes at when operated at grading unit speed of 4rpm, angle of inclination of -150 and feed rate which presented grading capacity of 3182kghr -1 , 93% efficiency and 3.02% mechanical damage.

Recommendations

Smallholder potato farmers could enhance their grading efficiency by procuring a variable pitch potato grader. Further, effects of low market price for potato produce could be minimised by improved quality, reduced grading time and lower cost of grading by operating the grader at grading unit speed of 4rpm, angle of inclination of -150 and 3400kghr -1 feed rate.

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