PERFORMANCE EVALUATION OF A PROTOTYPE VARIABLE PITCH IRISH POTATO GRADER

KIBOR DAVID TIROP

UNIVERSITY OF ELDORET

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KIBOR DAVID TIROP

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OCTOBER, 2023

DECLARATION

Declaration by the Candidate

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Kibor, David Tirop

________________________________ Date______________________

PG/ABE/001/12

Declaration by the Supervisors

We confirm that this thesis has been submitted with our approval as the university supervisors.

________________________________ Date______________________

Dr. (Eng) Solomon Mulindi Adekhela, PhD

University of Eldoret, Kenya

________________________________ Date______________________

Dr. Gilbert K. Ngetich, PhD

University of Eldoret, Kenya

DEDICATION

To my wife Janet and my children Barbara, Deborah and Laura for their unwavering support during this study.

ABSTRACT

The manual grading of potatoes in Kenya has resulted in inconsistencies, quality variations and financial losses for small-scale farmers due to low market prices for ungraded products. To mitigate these challenges, this study aimed to develop and evaluate the performance of a cost-effective potato grading machine to enhance uniformity and overall quality of potato tubers. The research involved determining the physical and mechanical properties of Shangi potato variety. The prototype potato 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 commendable grading capacity of 3968 kg/hr, with an efficiency of 89.34% and a low mechanical damage index of 2.94%. The results demonstrate that the potato grading machine effectively enhances grading while minimizing mechanical damage. This grading machine offers efficiency 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. Additionally, investigating alternative power sources may enhance the grader's versatility and extending testing to other fruits and vegetables would broaden its applicability in the agricultural industry.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

NPCK:	National Potato Council of Kenya
WTO:	World Trade Organization
FAO:	Food and Agriculture Organization
H.P:	Horse Power
MGD:	Mean geometric diameter
Kw:	Kilowatt
mm:	Millimeters
N-M:	Newton Meter(s)
M:	Meters
M/min:	Meters per minute
ANOVA:	Analysis of Variance
UoE:	University of Eldoret
GC:	Grading Capacity
GSE:	Grading System Efficiency
MDI:	Mechanical Damage Index
BeTA	Bottom-up Economic Transformation Agenda
MOA	Ministry of Agriculture

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CHAPTER ONE

INTRODUCTION

1.1 Background Information

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 (DeFauw *et al.*, 2012). 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 and is consumed almost daily by over a billion people (Wubet *et al.*, 2022). Global production of potato, over the last two decades, expanded from 267 to 375 million tonnes (Djaman *et al.*, 2021). Within 30 years, the average potato crop productivity in the continents of Africa, Asia and South America has increased by 44, 25 and 71 percent, respectively (Paredes *et al.*, 2018).

In Kenya, potato production and consumption are on the rise with the crop coming second to maize in terms of consumption (Adhikari *et al.*, 2015). In 2010, Kenya's potato production averaged 7700 kilograms per hectare annually with the main potato growing regions being, West Pokot and Elgeyo Marakwet (Nyasulu, 2021). According to NPCK (2017) there are 19 adapted potato varieties in Kenya with the Shangi variety being the most common and also a highly consumed variety due to its early maturity and high productivity. However, the number of varieties has increased to beyond 50 with the introduction of new cultivars 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 foodstuffs either at the household or at industrial level (Musita *et al., 2019*). Furthermore, processed potato products such as crisps and French fries which is commonly known locally as chips are on high demand among urban consumers and therefore 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.

The potato plays an important role in improving food security and cash income of smallholder potato growers due to its high yielding potential per hectare and nutritious tuber (Wijesinha-Bettoni and Mouillé, 2019). Potato is the second most important food crop in Kenya after maize and is mostly cultivated by smallholders. 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. The issue of food loss is an extremely important factor in securing the stable production required to fight starvation and increase household incomes. Once harvested, potatoes can be used for diverse purposes such as a fresh vegetable for cooking at home, as raw material for processing into food products, as animal feed, food ingredients, starch and alcohol production and as seed tubers for growing in the next season (López-Córdoba *et al.*, 2019).

Around the world, consumer demand is shifting from fresh tubers to processed products and therefore, more and more greater quantities of potatoes are being processed to meet rising demand for fast food and snacks (Iese *et al.*, 2018). As a result, a group of unit operations like washing, drying, sorting, grading, packaging and pre-cooling are performed after harvesting and before they reach the ultimate consumers (Mangaraj *et al.,* 2005; Shahir *et al.,* 2009). 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 *et al.,* 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).

1.2 Problem Statement

In Kenya, grading is mainly done manually by farmers, wholesalers, retailers and consumers through intensive labor input. Manual grading of potato tubers is often inconsistent since quality perception varies from one person to another; hence prone to human errors and variability. Potato quality evaluation has been done by trained human graders, but the unavailability of these inspectors has led to efforts to automate the process (Pedreshi *et al*., 2016). Furthermore, manual grading is costly, time-consuming and inefficient. Grading, based on the individual human being vision judgment is very poor and inefficient in terms of uniform product production (Patel *et al.,* 2012). Manual grading of potatoes takes a long time, and hence labor cost will be high and grading can be negatively affected due to scarcity of labor in peak seasons (Faqeerzada *et al*., 2018).

Due to various reasons stated above, most growers sell their products without grading and obtain very low prices (Reyes *et al.*, 2012). Conversely, the new marketing trends, adopted by World Trade Organization (WTO), demand high quality graded products (Margulis, 2018).

In order to sell potatoes to processors, regional and international markets as exporters; small and medium-scale farmers need to produce high quality and standardized products. Potato grading machines suitable for use on small-scale farms will help farmers respond to the emerging marketing opportunities positively through provision of high quality and standardized tubers suitable for the potato processing industry (Alemu, 2019).

1.3 Main objective of the study

The general objective of this research was to evaluate the performance of a prototype variable pitch Irish potato grading machine.

1.4 Specific Objectives of the Study

The specific objectives are:

1. To determine engineering properties of potato tubers – case study of shangi variety grown in Uasin Gishu County.
2. To evaluate the performance of a prototype variable pitch Irish potato grader.

1.5 Research Questions

1. What are the engineering properties of shangi potato variety?
2. What is the performance of the potato grader?

1.6 Justification of the Study

Grading of vegetables and fruits is one of the most important operations since it adds value to the product and gives better economic gain to the grower. Grading done based on size and form is important for selling uniform high-quality produce.

In this regard, the evaluation of performance of a potato grading machine that is appropriate for smallholder potato farmers' postharvest operations is important. This study, is consistent with the aim of BeTA, Vision 2030 and Agenda 63 and will significantly enhance processing, value addition and infrastructure development of potato value chains.

1.7 Significance of the study

The significance of this study is multifaceted and holds crucial implications for various stakeholders in the Kenyan potato industry. The manual grading of potato tubers in Kenya is prone to human errors and variations in quality perception. The study's focus on automating the grading process can lead to more consistent and accurate grading outcomes, ensuring that consumers and processors receive potatoes of higher quality. This will not only benefit consumers but also enhance the reputation of Kenyan potato products in regional and international markets.

Manual grading is not only costly but also inconsistent and time-consuming. By introducing automated grading machines, the study aims to reduce labor costs and the time required for grading. This will alleviate the financial burden on farmers, particularly during high demand periods when labor shortages can negatively impact grading efforts. Currently, many farmers in Kenya market their potatoes without grading, resulting in lower prices. However, international market trends, driven by organizations like the World Trade Organization (WTO), increasingly demand high-quality graded products. The study's findings can empower small and medium-scale farmers to meet these market demands, potentially leading to higher prices for their produce.

For Kenyan farmers looking to enter regional and international markets as exporters, the capability to produce high-quality and standardized potato products is paramount. The introduction of suitable grading machines for small-scale producers can enable these farmers to align with global quality standards, opening up new export opportunities and expanding their market reach.

The study can lead to new insights and knowledge in the field of potato grading technology, benefiting researchers and academia. It can also encourage further research avenues related to agricultural mechanization and food processing.

1.8 Scope and Limitations of the Study

This main study of evaluating the prototype was conducted based on potatoes from Uasin Gishu County on smallholder potato farmers producing Shangi potato variety. However, further trials were conducted at Molo ADC Seed Potato processing unit, Agrico farms in Nakuru County and KALRO in Tigoni, Kiambu County. Classification of the potatoes was based on small tuber diameter. Subsequently, the study adopted potato grading regime by NPCK 2019; thus, <35mm, 35-50mm, 50-80mm and >80mm which are consistent with market niches. The primary emphasis of the design was on achieving a functional system that efficiently grades the potatoes.

The engineering properties of shangi potato tubers considered were: Minor, intermediate and major diameters, frictional coefficients and repose angle. The performance evaluation of the grading machine was based on three key factors: grading efficiency, mechanical damage index and grading capacity; while, operational parameters included feed rate, angle of inclination, and grading unit speeds.

Some of the challenges in designing of the grading machine arose from variation in agronomic practices on the farms, weather conditions and genetic factors that led to variation in grading system efficiency.

CHAPTER TWO

LITERATURE REVIEW

2.1 Potato Production in Kenya

Potato farming is practiced by over 800,000 farmers in Kenya, due to its high lucrative value and is now the second most important food crop after maize. It generates employment for an estimated 2.5 million Kenyans both directly and indirectly along the value chain (Adhikari *et al.*, 2015). Improved potato production has the potential to significantly boost farm incomes especially after the recent introduction of disease-resistant and heat-tolerant varieties. Cultivation is concentrated in highland areas with altitudes ranging from 1200 to 3000 m above sea level (Kabira *et al.,* 2006). These areas include the slopes around Mt. Kenya, such as Meru, Embu, and Kirinyaga; parts of Laikipia and on both sides of the Aberdare Ranges that coves parts of Nyeri, Muranga, Kiambu and Nyandarua Counties. They are also grown in the highlands on Mau Escarpment; Mau Narok and Molo, Tinderet, Nandi Escarpment and Cherangani hills. Small areas are also cultivated in Kericho and Kisii Counties and isolated patches near the Coast in the Taita hills (Kirumba *et al*., 2004).

2.2 Physical Properties of Potato Tubers

Physical properties of agricultural materials are important for handling and processing operations and need to be easy and accurate to determine (Al-Juhaimi *et al*., 2018). These physical properties include size, shape, volume, density, moisture content, texture and mass.

The major difficulty associated with agricultural and food products is the variability in their sizes and shapes. Fruit and vegetable sizes can be characterized by means of physical parameters such as volume, weight, diameter, circumference, projected area, or any combination of these (Costa *et al*., 2011). Fruit and vegetable size determination allows the grading of fruits and tubers into different size groups; its classification into batches of uniform size. In many food processing applications and research problems, it is essential to have an accurate estimate of size and shape of the material. The design of grading and sizing machine, hydrodynamic and aerodynamic handling equipment and also the determination of thermal characteristics of a product are all common examples where size and shape of the product need be determined (Jahanbakhshi *et al.,* 2019).

Size of regular particles can easily be specified, but for irregular particles, the term size must be arbitrarily specified. Tuber size is mainly characterized by the equatorial or transverse diameters and the polar diameters or lengths. The device used to measure these diameters is digital caliper (Golmohammadi *et al.,* 2013). Size can also be determined using the projected area method. Three characteristic dimensions are defined as major diameter (the longest dimension of the maximum projected area), intermediate diameter (the minimum diameter of the maximum projected area or the maximum diameter of the minimum projected area) and minor diameter (which is the shortest dimension of the minimum projected area). Length, width, and thickness are commonly used as the alternative to major, intermediate, and minor diameters, respectively. The following figure shows how to measure triaxial ellipsoid (d_{max}, d_{inter} and d_{min}) food materials. In a triaxial ellipsoid all three perpendicular sections are ellipses (d_{max}=2a, d_{inter} = 2b, d_{min} = 2c; see Figure 1).

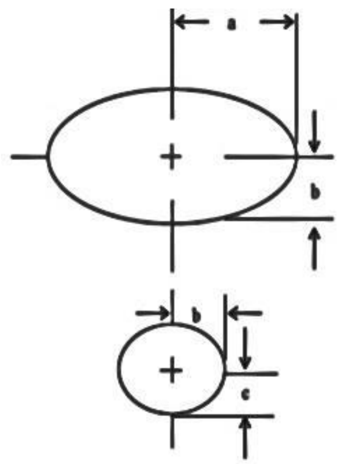

Figure 2.1: Measurement and representation of dimensions of triaxial ellipsoid body

a) Mean Geometric Diameter

The mean geometric diameter can be determined using equation (2.1) by Mohsenin in 1986 (Tabar *et al*, 2011).

$$d_g = (abc)^{1/3} \qquad (2.1)$$

where, d_g is mean geometric diameter of a sample (mm), a, major diameter (mm), b, intermediate diameter (mm) and c, minor diameter (mm)

Studies on methods dealing with surface area fall into three types of groups. The first general method assumes that the product can be defined as a standard geometric form and the surface area calculated from standard geometry equations. The second group involves empirical methods and the most commonly used approach is to relate weight to surface area.

a) Surface Area

The surface area can be calculated by weight relationships, counting squares or with the aid of a planimeter or can be estimated using equation 2.2 by Rha in 1975 and (Alemu, 2019).

$$S = \pi\left(d_g\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.2)$$

where, S is the surface area of a sample in mm^2 and d_g is the geometric mean diameter in mm.

The reference method for measuring the volume of vegetables is by water displacement based on Archimedes principle. In situations where fruit growth continues, it is preferable to estimate fruit (Mai & Wang, 2020).

b) Volume

The most commonly used method of determining the volume and specific gravity is the use of a platform scale. Both volume and specific gravity can be determined from the same data. The information needed includes the weight of the product in air, the weight of the container and water, and finally, the weight of the container, water and submerged product. The volume can be estimated using equation 2.3 by Mohsenin in 1986 (Orhevba & Jinadu, 2011).

$$Volume(m)^3 = \frac{Weight\ of\ displaced\ water(N)}{Unit\ weight\ of\ the\ water\left({}^{N}/_{m^3}\right)} \ldots\ldots\ldots\ldots \quad (2.3)$$

Another method used to determine the volume and area of the common shapes of fruit and vegetables resembling sphere, cylinder, brick, prolate spheroid, oblate spheroid, and frustum right cone can be determined using the formula in Table 2.1.

Table 2.1: Formulae used to determine the volume and area of the common shapes of fruit

Item	Shape	Area	Volume
1	Sphere	$= 4\pi r^2$	$= \frac{4}{3}\pi r^3$
2	Cylinder	$= 2\pi r^2 + 2\pi rL$	$= \pi r^2 L$
3	Cube	$= 6a^2$	$= a^2$
4	Brick	$= 2(ab + bc + ac)$	$= abc$
5	Prolate Spheroid	$= 2\pi b^2 + \frac{2\pi ab}{e}\sin^{-1} e$	$= \frac{4}{3}(\pi ab)^2$
6	Oblate Spheroid	$= 2\pi b^2 + \frac{\pi b^2}{e} ln\left(\frac{1+e}{1-e}\right)$	$= \frac{4}{3}\pi a^2 b$
7	Frustrum	$= \frac{\pi}{3}L(r_1^2 + r_1 r_2 + r_2^2)$	$= \pi(r_1 + r_2)\sqrt{L^2 + (r_1 + r_2)^2}$

Source: Satpute and Jagdale (2016)

c) Sphericity

The shape of an object can be determined by comparing the object with a set of standard shapes. Normally, the comparison is made of the projected images with a descriptive term assigned to each standard image (Mohsenin, 1968). The shape of an agricultural material is usually expressed in terms of its sphericity and aspect ratio. Sphericity or shape factor is the degree to which an object resembles a sphere. Assuming that the bulk of the solid sample is equivalent to the volume of the three axis ellipsoid with diameters equal to major, minor and intermediate diameter; thus, sphericity can be calculated using equation 2.4 as per Mohsenin in 1968 (Orhevba and Jinadu, 2011).

$$\varphi = \frac{\sqrt[3]{abc}}{a} \quad (2.4)$$

where; a, b and c are major, minor and intermediate diameters, respectively.

d) Moisture content

Moisture Content; Moisture content, w (%) of potato tubers can be estimated using oven dry method and using equation 2.5 (Asoegwu, 1995).

$$M_C = \frac{W_1 - W_2}{W_2} \quad \ldots\ldots\ldots\ldots \text{(2.5)}$$

where: M_c is the moisture content (% W_b), W_1 is the mass of potato tuber sample before oven-drying (g) and W_2 is the mass of potato tuber sample after oven-drying (g).

e) Mass

Measurement of weight is used for sorting vegetables because this parameter is closely related to size and volume. Weight can be determined using spring balance or digital balance from which mass can be measured and there after converted into weight.

f) Density

Tuber density is described as mass of a tuber divided to its actual volume, equation 2.6. Internal pores are included. If the size of the internal pores is negligible then, the solid density is equal to bulk density as per Mohsenin, 1986 (Orhevba and Jinadu, 2011).

$$\rho_{\mathcal{p}} = \frac{M_t(kg)}{V_t(m^3)} \quad \ldots\ldots\ldots\ldots \text{(2.6)}$$

Where, ρ_p is the particle density (kg/m^3), M_t mass of a tuber (g) and V_t volume of a tuber.

g) Bulk Density

Bulk density (ρ_{bulk}) is one of the most important physical properties. Density is defined as mass per unit volume of packed or stacked material equation 2.7 (Rahman, 2005). The bulk density of packed materials depends on the geometry, size, and surface properties of individual particles (Gupta and Larson, 1979).

$$\rho_{bulk} = \frac{mass(kg)}{volume(m^3)} \quad \text{(2.7)}$$

h) Specific Gravity

Two techniques are commonly used to measure Specific gravity (G_s). The most widely accepted method, and probably the more accurate, is to weigh a sample in air and in water. Samples should be sound, free of soil, because any hollow heart or adhering soil can affect the result. Equation 2.8 may be used to estimate the specific gravity of a material (Murthy, 2002).

$$G_s = \frac{Weight\ in\ air(N)}{Weight\ in\ air(N) - Weight\ in\ water(N)} \quad \text{(2.8)}$$

2.2.1 Mechanical Properties

Properties such as shape, size, roundness, sphericity, volume, density, coefficient of friction and mechanical properties like breaking force, deformation, cutting force puncture force are some of the important properties which play an important role in designing a specific machine as well as in the analysis of product behavior during handling.

a) Frictional Properties of Potato Tuber

The coefficients of static friction between potato tuber and different surfaces can determined by using equation 2.9 (Öztürk *et al.*, 2018).

$$\mu_s = \tan \alpha \quad \text{(2.9)}$$

where, μ_s is the coefficient of static friction and α is the angle of inclination at which samples of potato tuber start to slide down.

The coefficient of dynamic friction is determined using potato tubers in a topless and bottomless plywood box with dimensions of 250 × 250 × 90 mm^3. The box is placed on the test surface and filled with a known quantity of potato tubers and force was applied to plywood box until it moved consistently with a gentle pull. The friction test is replicated thrice for the surface under investigation. For each replication, the box is filled up with a different sample. The coefficient of dynamic friction can be calculated using Equation 2.10 (Puchalski *et al., 2003).*

$$\mu_d = \frac{F}{mg} \quad \ldots\ldots (2.10)$$

where, μ_d is the coefficient of dynamic friction, F is the friction force that will be measured using pull force gauge (N), m is the mass of the sample (kg) and g the gravitational acceleration (m/s^2).

b) Angle of repose

The properties of particles forming the medium (dimensions, shape, surface frictional and deformation ability) influence the value of repose angle (Al-Hashemi *et al.*, 2018). The angle of natural repose is the slope formed between the base of a pile and its inclined surface. Clean potato tubers stored in bulk storage has a repose angle of 37° (Eltawil, 2006). When removing potatoes from the face of this pile, a new, steeper, unstable angle of repose will be created at about 45 degrees from horizontal (Irvine *et al.*, 1993). The naturally occurring stable slope angle from horizontal that an open face of a potato tuber will make is estimated from the trigonometric relationship as shown in Equation 2.11 (Irvine *et al*., 1993).

$$\propto = tan^{1}\left(\frac{height\ of\ pile}{base\ length\ of\ pile/_{2}}\right) \ldots\ldots (2.11)$$

2.3 Potato Grading

Grading of vegetables including potatoes is an important operation affecting quality, handling and storage of produce and plays a major role in the food processing industries. Grading is done to standardize a product, to facilitate marketing, for sales appeal, for ease in quantifying, for ease in price fixing of uniform sized lot and for compliance of international or national grading standards (Sumari *et al.*, 2018). In this regard, every vegetable producing country has its own standards for different grades in view the market requirements (Ridolfi *et al*., 2018).

2.3.1 Importance of Grading

Grading plays a vital role in the potato marketing process. It offers several benefits, including determining the price for potato producers and sellers, reducing marketing costs, ensuring fair prices for consumers, and creating opportunities for potato exports. Grading also influences the utilization of potatoes, as smaller to medium-sized tubers are ideal for seed purposes, while larger tubers are more appropriate for processing.

2.4 Testing, Performance and Evaluation of Potato Graders

2.4.1 Crop parameters

Mahirang *et al.,* (2009) provided a basis on the classification of potato tubers as small, medium and large with minor diameters of 30-39 mm, 40-74 mm and 75 mm and above respectively (Valentin *et al*, 2016). According to Swarnalakshmi and Kanchanadevi (2014) potato tubers with diameter ≥60 mm are considered as big but small when the diameter is ≤50 mm. The large size potato tubers are used for processing, especially for making chips and for roasting. Medium and small size potato tubers are preferred for cooking. Seed potato tubers are preferred to have diameters between 28mm and 55mm and are normally graded into two sizes of 28mm to 40mm (regarded as small potato seed) and 40mm to 55mm as large potato seed (Mumia *et al., 2018*). According to Garba *et al.,* (2009) tubers of uniform size, ranging from 25mm to 50mm can be used as planting material.

2.4.2 Grading Gaps

Peleg (1985) model for estimating grading apertures is given in equation 2.12.

$$X_{12} = \left[\frac{\mu_2\sigma_1^2-\mu_1\sigma_2^2}{\sigma_1^2-\sigma_2^2}\right] \pm \left[\left(\frac{\mu_2\sigma_1^2-\mu_1\sigma_2^2}{\sigma_1^2-\sigma_2^2}\right)^2 - \frac{\mu_2^2\sigma_1^2-\mu_1^2\sigma_2^2-2\sigma_1^2\sigma_2^2\ ln\left(\frac{\sigma_1}{\sigma_2}\right)}{\sigma_1^2-\sigma_2^2}\right]^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.12)$$

where; X_{12} is the grading pitch of the diameter of separation point between potato tuber sizes 1 and 2, μ_1 and μ_2 are the mean geometric diameters of potato tuber sizes 1 and 2. Also, σ_1 and σ_2 are the standard deviation of the mean geometric diameters of the potato tuber sizes.

2.4.3 Grading capacity

Grading capacity of potato tuber grader can be determined on the basis the amount of potato tubers graded within a specific period of time as suggested by Cochran and Cox in 1975, can be used to estimate graders capacities (Mishra *et al.*, 2020).

$$Grading\ Capacity\ (kg.hr^{1}) = \frac{Weight\ of\ graded\ tubers\ (kg)}{Total\ time\ taken\ to\ grade\ (hr)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2.13)$$

2.4.4 Grading system efficiency

The grading efficiency is determined by comparing observed weight and the expected weight of the potato tubers in each tray and efficiency determined using the root mean square error method depicted in equation 2.14. Lower RMSE values reflect a better model in terms of its absolute deviation (Brkic *et al.*, 2019).

$$RMSE = 100 * \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2.14)$$

where; x_i is the expected weight, μ 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.

2.4.5 Grading Damage

Damage of tubers with abrasion after the grading operation can be considered. The percentage of damaged tubers is taken by considering the total number of tubers with abrasion after the operation against the total number of tubers in the sample as indicated in Equation 2.15.

$$Damaged\ tuber(\%) = \left(\frac{Total\ no.of\ tuber\ with\ abrasion}{Total\ no.of\ tuber\ in\ \text{sample}}\right).100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2.15)$$

An understanding of the mechanical characteristics of potato tubers may improve harvest and postharvest operation and reduce economic losses. Mechanical impact, during harvesting and postharvest processes, causes external as well as internal damage to agricultural and horticultural products. This damage decreases the quality of the product. Increased mechanization and accelerated flow rates of the produces during harvesting and postharvest processes increase the mechanical impact and thus increase product losses.

Research reports indicate that tuber damage relates primarily to the magnitude of impact energy and to the susceptibility of a particular cultivar. Tuber damage, or bruise, has generally been divided as shatter bruise (externally visible) and black spot bruise (internal cracking, crushing and discoloration). Resistance to these two types of damage is primarily influenced by tuber hydration levels at the time of impact and by genotype (Strehmel *et al*., 2010).

2.5 Potato Grading Methods and Machines

Around the world, various types of potato grading equipment have been created in response to consumer demand and processing considerations. Grading typically takes into account factors like size, shape, weight, color, etc. Various studies were conducted to ascertain how various grader types were applied when categorizing various kinds of vegetables and other agricultural products. (Londhe *et al.*, 2013).

Potato grading can be done using both manual and mechanized methods. There are several practices that are usually used for grading potatoes. First, manual grading which involves utilizing a set of rectangular sieves with round holes of different diameters. Two individuals shake the sieves placed one above the other, while a third person continuously feeds the upper sieve with potatoes. Another manual method involves hanging sieves on chains or ropes that move back and forth to grade the potatoes. Mechanical graders are also utilized for potato grading. These graders feature sieves mounted on an oscillating frame, which is mechanically operated by power. The mechanical grader can be powered by an electric motor, engine, or tractor, providing efficient grading capabilities. Additionally, power-operated potato graders with a conveyor attachment offer enhanced grading efficiency, reaching up to 90% (Jacob. P, 2008). These graders have a power requirement of 1.5 H.P and can classify potatoes into four categories based on weight: less than 10 grams, 10-25 grams, 25-60 grams, and more than 60 grams.

2.5.1 Grading by Size

Grover and Pathak in 1972 developed a potato grader with wire belt type grading mechanism, driven by an electric motor and able to grade potato tubers into four main sizes. The grading machine was evaluated and the output was found to be 2000 to $2400 kg.hr^{-1}$ with 1.00% to 10.00% of bruising and about 94% of grading efficiency (Londhe *et al*., 2013).

An expanding gap type rubber spool potato grader consisting of mainly of a grading conveyor containing a rubber spool and two identical driving rollers with helical grooves of gradually increasing gap was designed and constructed to categorize potato tubers into various size grades. The performance of this grader was investigated at three different speed of sizing bed conforming to the helical shaft speed of 190, 110, and 75rpm. The outcome revealed that there was no significant difference in weight collected at different size categories at different shaft speeds (Londhe *et al*., 2013).

A differential belt speed expanding pitch type potato tuber grader consisting of feeding conveyor, chassis, grading unit, collection trays and power source was developed and tested by (Londhe *et al*., 2013). The grader required 1hp electric motor to drive its various mechanisms at full load. The maximum grading efficiency at optimum grader shaft speed of 35 rpm, belt speed of 0.073 $m.s^{-1}$ and feed rate of 1724$kg.hr^{-1}$ was found to be 87.00%.

A low cost, rotary disc type grader was developed for grading spherical agricultural products using rubber spheres of different diameters in the laboratory. It was learned that the disc speeds between 60 and 70 rpm were the most efficient for separation of different grades (Sidhu *et al*., 2015).

Widodo *et al.*, (2012) developed and performed the evaluation of a fruit and vegetable grader. The functional units of the machine were a take-in conveyor, grading unit and take-away conveyor, and a frame on which all the components mounted. To optimize the feed rate of the grader, three take-in conveyor speeds of 0.17, 0.25 and 0.33 m/s were selected with feed/load rates of 6000, 9000 and 12000 $kg.hr^{-1}$, respectively. A drive mechanism with three speed levels 25, 50 and 75 rpm were tried to accommodate the different feed rates. The packing point take-away conveyors were operated at three speeds, 0.083, 0.167 and 0.25 $m.s^{-1}$ without causing mutual collusion of the falling produce from grading unit. Increased grading speed of 75 rpm resulted in increased damage index whereas higher take-in conveyor speed 0.33 $m.s^{-1}$ resulted in more non-uniformity of grading.

Alemu, Fanta, and Getnet (2021) developed helix type potato grader consisting of a hopper, grading unit, prime mover and catchment tray mounted on a steel chassis. The hopper served as a guide for the potato tubers to the grading unit. The grading unit is a spiral type with increasing gap starting from the inlet. The spiral assembly has three sections: the region for small, medium and large-sized tubers. The first region has gaps that allowed only small tubers to pass. The gap of the spiral for this region ranged from 3.0 cm to 3.9 cm. The second region had gaps of 4.0 cm up to 7.4 cm allowing medium sized tubers to pass. The third was the region for the large tubers with gaps greater than 7.5 cm. The performance of this potato tuber grader was evaluated in terms of grading system efficiency (percent), capacity ($kg.hr^{-1}$), percentage damaged tubers and power consumption at three different speeds (10, 15 and 20 rpm) and at three inclinations of the grading unit (5, 10 and 15°). Results of the performance evaluation indicated that the grader had optimum performance when it was operated at 15 rpm and inclination of 10 degrees with a system efficiency of 92.56%, and grading capacity of 441.58 $kg.hr^{-1}$, tubers damaged of 1.83% and power consumption of 22.6 W.hr which was the least.

2.5.2 Grading by Weight

A multipurpose grader capable of grading fruits into four grades (A, B, C and D) on basis of weight was designed and developed. Sizes were classified as Grade A (>200 g), Grade

B (150-200 g), Grade C (100-150 g) and Grade D (<100 g). The performance of the grader was evaluated at different speeds of 5, 10, 15, 20, 25 and 30 rpm. It was found to be suitable at carrier speeds between 12 and 15 rpm with overall grading efficiency of about 96% (Sravan and Tejaswini, 2020).

2.5.3 Grading by Screen or Sieve

Studies conducted to assess the effect of various parameters on the performance of an experimental power operated sieve potato tuber grading machine capable of grading tubers into four different size grades by mechanical sieving indicated that, screening efficiency and blinding increased with decreasing sieve speed, stroke length and sieve slope while screen efficiency increased with decreasing feed rate but decreased as the feed rate progressively increased. High screening efficiency up to 93.67% was obtained by providing slight manual assistance to take care of blinding of sieves. However, tuber damage was consistently high (Sravan and Tejaswini, 2020).

A simple both manual and power operated mechanical sieve grader with and without feed conveyor attachments used for grading seed potato tubers was developed by Shyam and Singh in 1988 (Londhe *et al*., 2013). The grader used the conventional principle of sieving. It comprised of a steel frame, a set of oscillating sieves, a power transmission unit, a stationary sieve feeding chute, a sorting platform and a bag filling chute. The grader was powered by one horsepower 3-phase electric motor. The yield capacity was found to be 600 $kg.hr^{-1}$.

A low-cost potato tuber grader with three sieves inclined at an angle of 15° from the horizontal and sieves made of rubber net was developed and tested. The grader was capable of grading potato tubers into four sizes with a throughput capacity of 2,030 $kg.hr^{-1}$. Trapping of potato tubers in the sieves was observed and to eliminate the potato tuber trapping, a mechanism for re-orientation of potato tubers was recommended (Londhe *et al.*, 2013).

2.6 Summary of Literature Review and Research Gaps

From literature review made, it was noted that potato plays an important role in improving food security and cash income of smallholder potato growers of Kenyan farmers due to its high yield potential per hectare and nutritious tuber.

Different research report indicated that grading is one of the most important operations performed after harvesting and reaches the ultimate consumers which add value to the product and gives higher economic gain to the producers. Grading of vegetables on the basis of size and shape is important for marketing uniform high-quality produce.

According to research findings, physical properties of agricultural materials and food products are important in many grains/seeds and vegetables, and food materials handling and processing operation. It is reported that rapid and accurate determinations of physical properties are needed in processing agricultural materials.

Different potato grading machines were developed around the world. Studies made by different researchers on the performance of potato tubers, fruits and vegetables grades was based on grading capacity, grading efficiency and mechanical damage. Table 2.2 shows gaps in the previous studies.

Table 2.2: Research gaps

No	Author(S)	Title	Remarks and Research Gaps
1	Alemu (2019).	Design, Manufacturing and Performance Evaluation of Potato Grading Machine.	The researcher did not consider the use of feeding conveyor mechanism to control the feed rate.
2	Mostafa *et al* (2009)	Development of Affordable Machine for Sizing Egyptian Onion	The study did not consider for grading of potatoes
3	LIU *et al.* (2022)	Parameter Optimization for a Potato Rod-type Conveyor Grading Device Based on the Discrete Element Method	The parameters of the potato model were extracted from relevant literature, and it was impossible to guarantee full consistency between the discrete element model for potatoes and the actual distribution of potatoes adopted in the test. All these factors might have contributed to the differences between simulation results and measured values.
4	Ghanbarian *et al* (2008)	Design And Development Of A Small Potato-Grading Machine Using Capron Net	To obtain maximum accuracy of grading, the tubers must be in a single layer on the grading surface; otherwise, the accuracy of grading is rapidly decreased.
5	Bayboboev *et al* (2021)	Substantiation and calculation of gaps of the separating working bodies of machines for cleaning tubers.	The calculations carried out were of a general nature and were performed with respect to potato varieties by the average value of the sizes and weights of tubers of the most common potato varieties. Variation in dimensional characteristics of potato tubers was necessary to select the rational size of the separating organs when designing machines for potato growing.

2.7 Conceptual Framework

A conceptual framework serves as a tool for analyzing the relationship between independent and dependent variables, taking into account factors like moderating and intervening variables (Bryman and Bell, 2022). It is a versatile tool that can be applied across various domains to provide a comprehensive understanding. Conceptual frameworks aid in making conceptual distinctions and structuring ideas. Effective conceptual frameworks accurately represent real-world phenomena and are easily applicable and memorable. In Figure 2.2 of this study, the specific conceptual framework utilized is depicted.

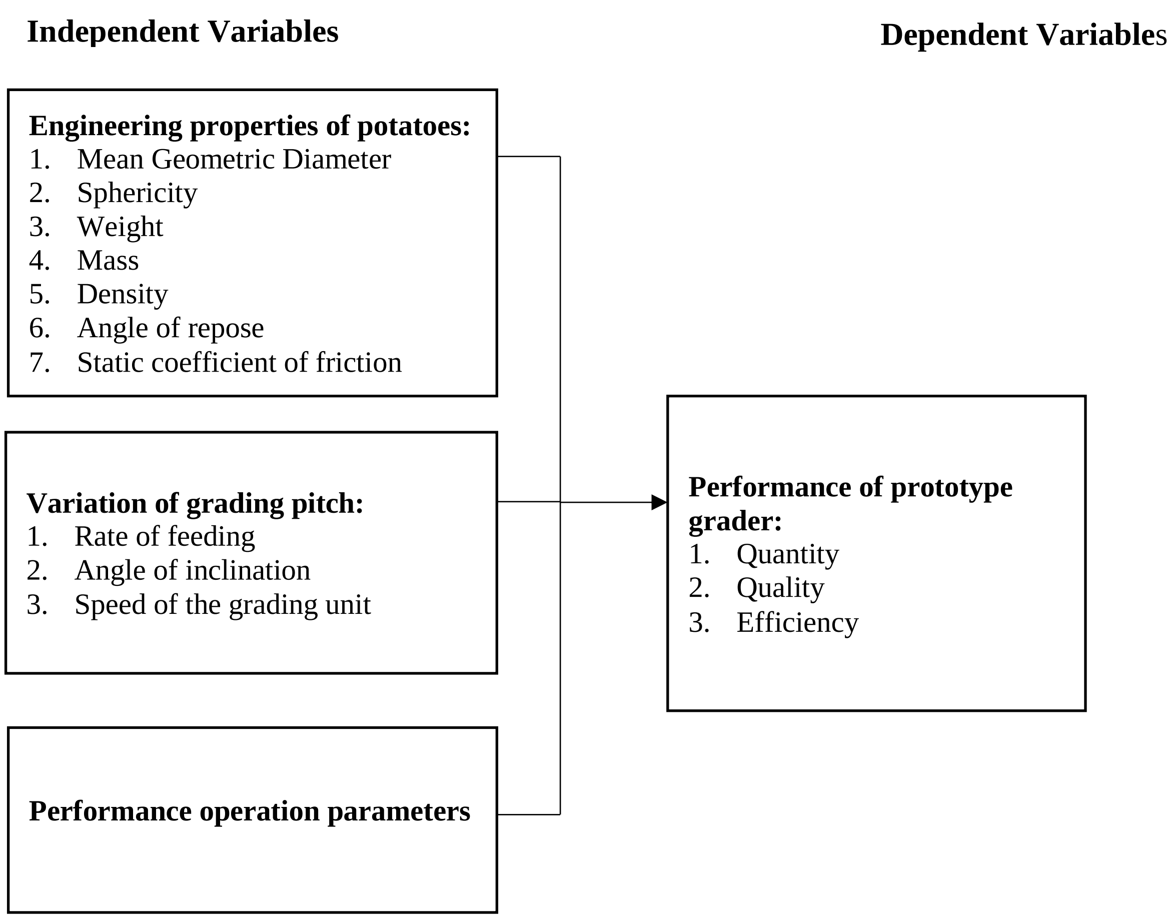

Figure 2.2: Conceptual framework

CHAPTER THREE

METHODOLOGY

3.1 The Study Prototype Potato Grader

The prototype potato grade under study was developed by Kibor *et al.*, (2021) to assist small holder farmers in Uasin Gishu County to mechanize potato grading. The grader is presented in Plate 3.1 and is further illustrated in Appendix IX.

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

The frame supports the entire weight of the grading machine. This weight include; that of the grading unit, feed hopper, pulleys motor drive chains, gear box and the potato tubers. The machine comprised of 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.

In this study it was assumed that the flow of material during the grading process is uni-directional, that is, backflow is negligible. In addition, the cylindrical shape of the grading unit parts has negligible effect on bruising and mechanical damage of the potato tubers. The curvature of the receiving trays was designed to minimize physical damage on the tubers.

The general flow of material is as illustrated in the Figure 3.1 below using the proto type potato grader given in Plate 3.1.

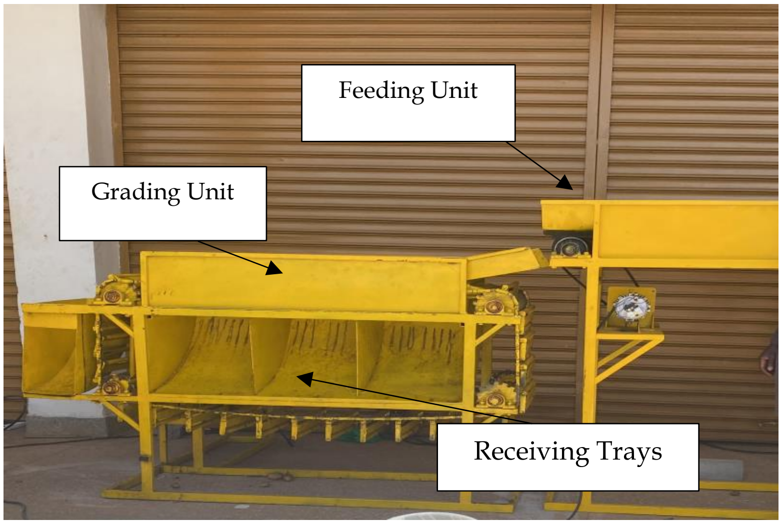

Plate 3.1: Proto type Potato grader

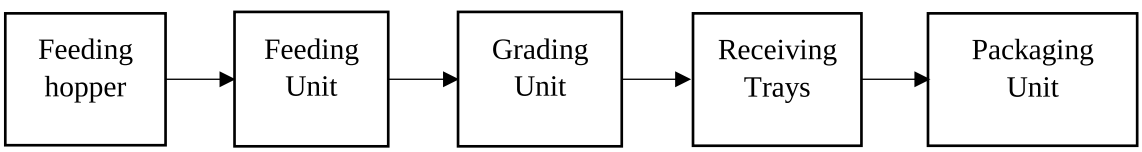

Figure 3.1: Potato Grader flow block diagram

3.1.1 Potato Grading Based on the Mean Geometric Diameters

The results of the characterization of the potato tubers gave the geometric sizes which were used to compute and set the grading aperture sizes using Peleg's (1985) model for estimating grading apertures given in equation 3.1.

$$X_{12} = \left[\frac{\mu_2\sigma_1^2 - \mu_1\sigma_2^2}{\sigma_1^2 - \sigma_2^2}\right] \pm \left[\left(\frac{\mu_2\sigma_1^2 - \mu_1\sigma_2^2}{\sigma_1^2 - \sigma_2^2}\right)^2 - \frac{\mu_2^2\sigma_1^2 - \mu_1^2\sigma_2^2 - 2\sigma_1^2\sigma_2^2 \ln\left(\frac{\sigma_1}{\sigma_2}\right)}{\sigma_1^2 - \sigma_2^2}\right]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

where; X_{12} is the grading pitch of the diameter of separation point between potato tuber sizes 1 and 2, μ_1 and μ_2 are the mean geometric diameters of potato tuber sizes 1 and 2. Also, σ_1 and σ_2 are the standard deviation of the mean geometric diameters of the potato tuber sizes.

Further, the tuber sizes for marketing recommended by NPCK 2019 (see Table 3.1), were reviewed and compared to sizes of tubers that the computed aperture sizes would yield to and the design of the grading unit and refined to be in line with the recommended standards and accommodate the tuber sizes available in smallholder farms. The Table 3.1 below shows potato size range and their associated use.

Table 3.1: The size range of potatoes and its associated common use

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

Source: NPCK (2019)

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

The grading machine was operated on the principles of a rotating grading unit with a variable pitch. The feeding unit was placed such that it fed the tubers onto a hopper on the grading unit. The grading unit is 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 machine is to grade the potatoes by their mean geometric diameters 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. The hopper was mounted at an angle which is greater than the repose angle of Shangi variety of potatoes on sheet metal.

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.

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.

3.2 Evaluation of Physical Characteristics of Irish Potato Tubers in Uasin Gishu County

This study examined the physical characteristics of the potato variety *Shangi*, 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. 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.

3.2.1 Determination of Potato Sizes

Plate 3.2 shows the image of a vernier caliper that was used to measure three perpendicular axes for each tuber with 0.01mm accuracy.

Plate 3.2: Image of a vernier caliper

3.2.2 Determination Weight of Tubers

The weight of each of the tubers was measured on an electronic balance to 0. 01g accuracy. The electronic weighing scale used is as depicted in Plate 3.3 below

Plate 3.3: Image of an electronic weighing scale

3.2.3 Determination of Coefficient of static friction

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 measured a protractor and the results recorded. The process was replicated three times using different samples of potatoes an average was then determined using equation 2.9.

3.2.4 Coefficient of static friction

The coefficient of dynamic friction was obtained using a topless and bottomless wooden box with dimensions 250*250*90 mm. The box was placed on the test surface and filled with 10kg quantity of potato tubers, a horizontal force was applied on the wooden box until it moved uniformly (Puchalski *et al., 2003)*. The test was replicated three times and average obtained. The coefficient was then determined using equation 2.10 as recommended by Amin *et al*., (2004).

3.2.5 Angle of Repose

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 equation 2.11 used to determine the angle of repose.

3.3 Performance Evaluation of Prototype Irish Potato Grading Machine

The performance of the prototype potato tuber grader was evaluated based Grading capacity, grading efficiency and mechanical damage. The independent variables used to evaluate the grader were grading unit speeds, feed rate and inclination angle.

3.3.1 Material Preparation

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. Five 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 0.01 mm accuracy. The weight of each tuber was measured on an electric balance to 0.01g.

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.

3.3.2 Determination of The Optimum Feed Rate, Inclination Angle and Speed of the Prototype Potato Grader's Capacity and Efficiency

The experiment was laid in a split-split plot design having grading unit speeds as the main plots, the angle of inclination and feeding rates as sub-plots and with three replications as a block. The design was 3^3 factional combinations with three replicates giving 81 total experiments. The treatments were three levels of grading unit speeds of (6 rpm, 4 rpm and 2 rpm), three levels of angle of inclination (-15^0, 0^0 and 15^0) and 3 levels of feeding rates of 3400 $kg.hr^{-1}$, 4000 $kg.hr^{-1}$ and 4600 $kg.hr^{-1}$.

The independent variables are speed of grading unit (6, 4 and 2 rpm) inclination of the grading unit (-5^0, 0^0 and $15^{0)}$) 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.

3.3.3 Effect of speeds, angle of inclination and feeding rates on Grading capacity, Efficiency and Damage index

a) Grading Capacity

The grader capacity was determined based on the amount of the potato tubers graded within a specified period as given by equation 3.2 below.

$$Grading\ Capacity\ (kg.hr^1) = \frac{Weight\ of\ graded\ tubers\ (kg)}{Total\ time\ taken\ to\ grade\ (hr)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

The results are presented and discussed in Table 4.3

b) 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.

$$RMSE = 100 * \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} \ldots\ldots\ldots\ldots\ldots\ldots \text{(3.3)}$$

Where; x_i is the expected weight, μ 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).

c) Mechanical Damage Index.

This was estimated by the fraction of the total weight of damaged potatoes verse the weight of the potatoes in the tray as given by equation 3.4

$$Damaged\ Index, DI(\%) = \left(\frac{Total\ no.of\ tubers\ with\ abrasion}{Total\ no.of\ tubers\ in\ \text{sample}}\right).100 \ldots\ldots\ldots \text{(3.4)}$$

This was repeated for every replication and data is presented in Table 4.3

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 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 on the Table 4.1 below.

Table 4.1: Physical properties of Shangi potato tubers

S/no.	Property	Mean	Std Dev.	Variance	CV%	Min	Max
1	Major Diameter (mm)	53.913	12.072	145.525	22.391	27.000	111.000
2	Inter Diameter (mm)	43.362	7.789	60.589	17.963	24.000	73.000
3	Minor Diameter (mm)	36.620	6.380	40.648	17.422	21.000	59.000
4	Mass (Grams)	55.877	33.374	1112.294	59.727	12.000	387.000
5	Mean Geometric Diameter (mm)	43.934	7.681	58.912	17.482	25.275	74.506
6	Surface Area (cm^2)	0.625	0.226	5.10E+4	36.171	0.201	1.74E+4
7	Volume (cm^3)	0.486	0.277	7.64E+5	56.904	8.45	2.16E+2
8	Sphericity	0.825	0.077	0.006	9.335	0.591	1.000
9	Density (Kg/M^3)	1.168	0.233	0.054	19.982	0.400	5.478

4.1.1 Size distribution of shangi potatoes

The Figure 4.1 shows the size distribution of shangi potatoes grown in Uasin Gishu County.

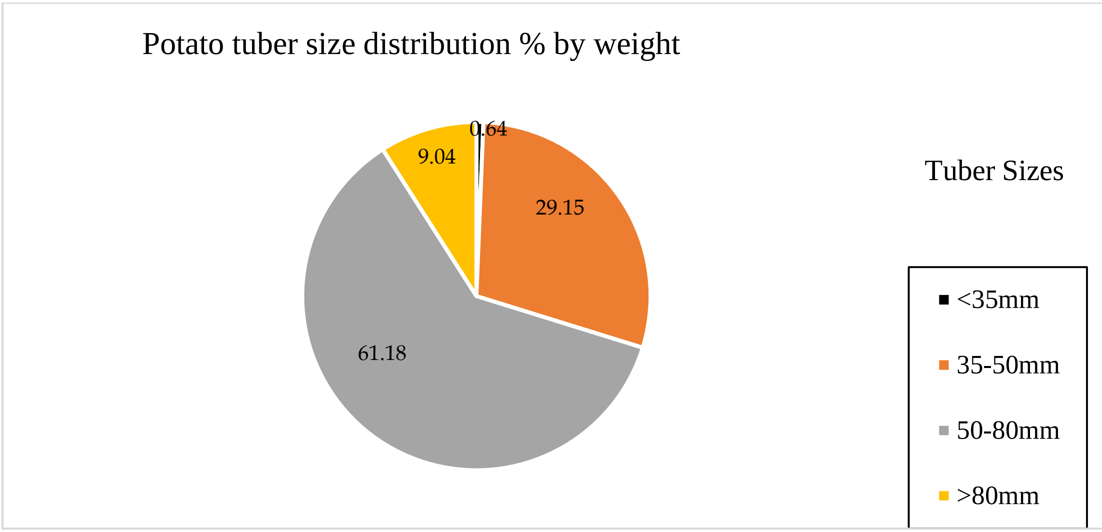

Figure 4.1: Size distribution of shangi potatoes

4.1.2 Mechanical Properties

The angle of repose ranged from 21.53^0 and 29.72^0 on sheet metal and 22.64^0 to 31.23^0 on rubber surface. The maximum and minimum angle of repose was recorded as 21.53^0 and 31.23^0 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.

4.2 Performance Evaluation of the Prototype Potato Grader

The equation 3.1 in conjunction with results from objective one; physical properties of potato tubers, the various aperture sizes for attaining the NPCK recommended size categories of potato tubers was used and the outcomes recorded in Table 4.2 below.

Table 4.2: Grading Unit Gaps

NPCK Recommended Potato Tuber Sizes (mm)	MGD	STD. DEV	Corresponding Variable pitch opening (mm)
<35	30.3	2.61	0-23.28
35-50	38.03	3.77	23.28-33.95
50-80	47.31	5.57	33.95-55.14
>80	62.66	5.22	>55.14

4.2.1 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 4.3.

Table 4.3: Interaction effect of grading unit speeds, angle of inclination and feed rate on grading capacity, grading efficiency and mechanical damage index

		Feed Rate (Kg/Hr)								
Speed	**Angle**	**3400**			**4000**			**4600**		
(RPM)	**(Ø)**	**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

a) Grading Capacity

The statistical analysis and ANOVA 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 effect of both grading unit speeds and feeding rates during grading process of Irish potato tubers on the prototype potato machines' grading capacity in $Kg.hr^{-1}$ are shown in Figure 4.2. It appeared that, increasing grading unit speed during the grading process from 2 - 6 rpm at all considered levels of feeding rates ranging from 3400 - 4600 $Kg.hr^{-1}$

produced a corresponding increase in the machine grading capacity. The maximum grading capacity of 4417.50 $Kg.hr^{-1}$ was recorded during the grading process at grading speed of 6 rpm and feeding rate of 4600 $Kg.hr^{-1}$. On the other hand, the lowest grading capacity was 2788 $Kg.hr^{-1}$ at grading unit speed of 2 rpm and feeding rate of 3400 $Kg.hr^{-1}$. This increase in machine grading capacity by increasing grading unit speeds may be attributed to the increase of potato tuber speed which resulted in reducing the time of grading and consequently increasing the grading capacity. In other words, increasing the speed of grading unit increases the throughput of potato tubers from the openings which in turn, increase the machine grading capacity. The figure 4.2 shows the combined effect of grading unit speeds and feed rate on grading capacity of the proto type potato grader.

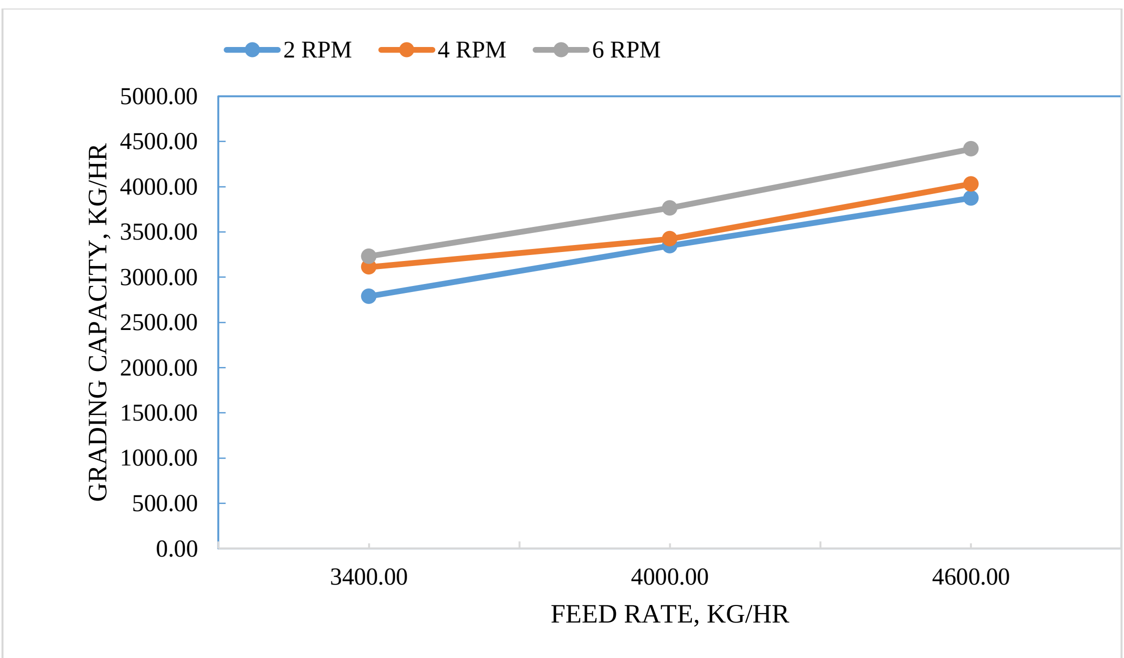

Figure 4.2: Effect of grading unit speeds and feed rate on grading capacity of the proto type potato grader

A maximum grading capacity of 4417.50 $Kghr^{-1}$ was achieved when the feed rate was $4600kghr^{-1}$, angle of inclination 0^0 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:

$$GC = 108.78\omega + 0.295\emptyset - 0.82Q - 200.56 \quad (4.1)$$

Where: GC = Grading Capacity, $kg.hr^{-1}$, □ = Grading Unit speed, rpm, Ø = Angle of Inclination, degrees and Q = Feed Rate, $kg.hr^{-1}$

b) Grading Efficiency

The statistical analysis, ANOVA showed that the grading unit speeds and angle of inclination had significant influence ($P<0.05$) on the grading efficiency. However, the feed rate had no significant influence.

Data demonstrated in Figure 4.3 shows that the percentage of grading efficiency of tubers was affected by different experimental variables. The results revealed that, at any grading speed ranging from 2 to 6 rpm, the grading efficiency decreased as inclination angles were increased from -15^0 to 15^0. However, at -15^0 inclination angle, the grading efficiency tended to increase from 86.82% to 93.34% as grading unit speed was increased from 2 rpm to 4 rpm. Further, the efficiency also increased from 89.72% to 93.34% as grading unit speed was decreased from 6 rpm to 4 rpm. On the other hand, the results revealed a marked reduction of grading efficiency at 6 rpm grading unit speed. This decrease in the grading efficiency especially at the higher grading speed may be due to the increase in the speed of the potato tuber displacement, which, in turn shortened the time of grading, which makes it difficult for penetration of potatoes through the apertures. The figure 4.3 shows the combined effect of grading unit speeds and angle of inclination on grading efficiency of the proto type potato grader.

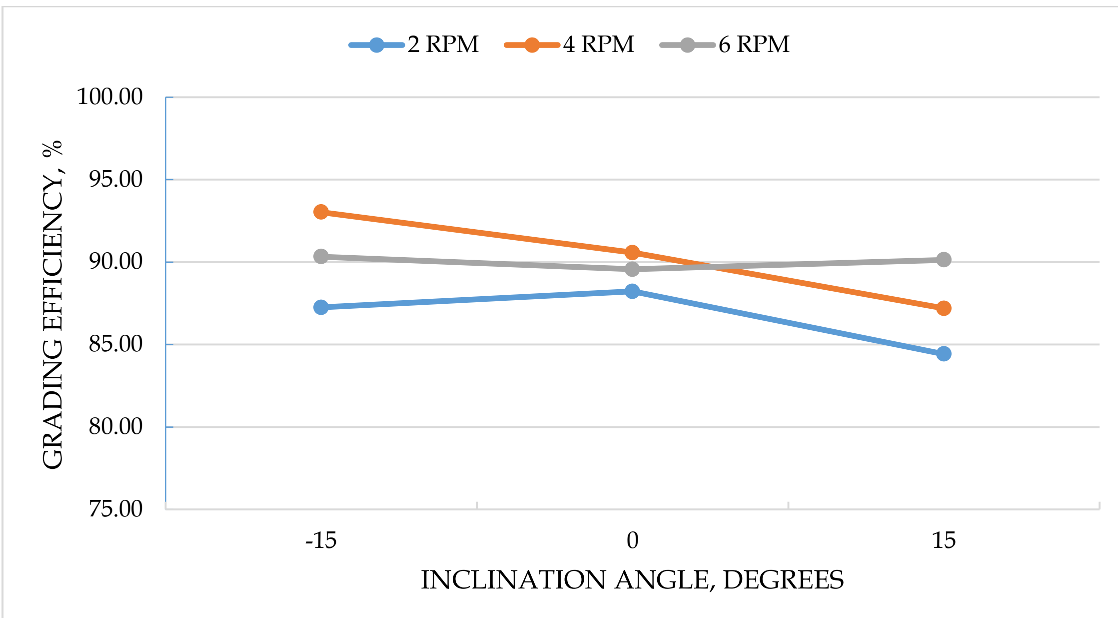

Figure 4.3: Effect of grading unit speeds and angle of inclination on grading efficiency of the proto type potato grader

Highest efficiency was observed at 93.34%and 93.18% when the grader was at feeding rate of 3400 and 4600 kghr-^{1}, angle of -15^{0} 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 *Qingshu 9* 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.

Conversely, the lowest grading efficiency was noted when the grading unit speed was at 2 rpm, angle of inclination 15^0 and feed rate of $4600 kg.hr^{-1}$, 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. The regression equation is represented as follows:

$$GE = 87.0 + 0.645\omega - 0.078\emptyset - 0.0001Q \qquad (4.2)$$

c) 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.

Data presented in Figure 4.4 show the mechanical damage percentage as affected by different levels of grading unit speeds and different levels of potato tuber feeding rates. It can be seen that, the mechanical damage percentage of potato tubers increased gradually as the feeding rates increased from $3400 kg.hr^{-1}$ to $4600 kg.hr^{-1}$ and as grading speed increased from 2 rpm to 6 rpm during grading. The data indicated that, increasing the grading unit speeds from 2 rpm, 4 rpm and 6 rpm caused an increase in the total mechanical damage from 1.86% to 4.60%; from 1.94% to 3.92% and from 2.47% to

5.37% at feeding rates of 3400 kg.hr^{-1}, 4000 kg.hr^{-1} and 4600 kg.hr^{-1}, respectively. Meanwhile, as the grading unit speeds increased from 2 rpm to 6 rpm, the increase in the tuber mechanical damage percentage was observed when grading tubers at 4600 kg.hr^{-1} feed rate, which was increased from 2.47% to 5.37%. This damaged value is more than the values equivalent to the total marketable yield quality. This increase may be ascribed to the increase in rolling action of potato tubers, which is associated with the increased the impact time of the tubers. In addition, potatoes may not sustain the impact. Therefore, the injuries may have also occurred when the tubers knock each other during the grading process. In general, the best allowable mechanical damaged of potato tubers (3.02, %) was obtained at 4 rpm grading unit speed and 3400 kg.hr^{-1} feeding rate during the grading process of potato tubers.

The Figure 4.4 shows the combined effect of grading unit speeds and feed rate on mechanical damage of the proto type potato grader.

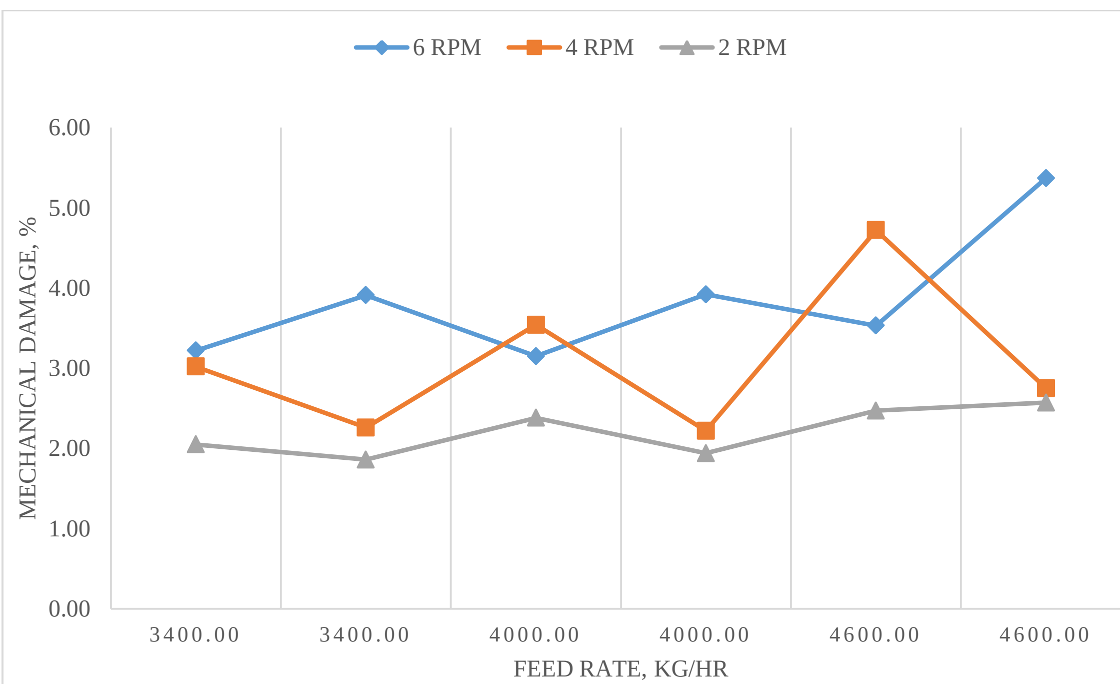

Figure 4.4: Effect of grading unit speeds and feed rate on grading capacity of the proto type potato grader

The lowest damage is observed at 1.86%, when the grader was set at 3400kghr^{-1} feed rate and angle of inclination of 15^{0} 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}, 15^{0} 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.

$$\mathrm{MD} = 0.31\omega - 0.005\emptyset + 0.0005\mathrm{Q} - 0.26 \qquad (4.3)$$

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

1. 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 21.53^0 and 31.23^0 for repose angle, 0.21 to 0.39 and 0.39 to 0.68 for static and dynamic coefficients of friction respectively.

2. The variable pitch potato grader was efficient and is appropriate for grading potatoes at when operated at grading unit speed of 4rpm, angle of inclination of -15^0 and feed rate which presented grading capacity of 3182kghr $^{-1}$, 93% efficiency and 3.02% mechanical damage.

5.2 Recommendation

5.2.1 Recommendation from the study

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 -15^0 and 3400kghr $^{-1}$ feed rate.

5.2.2 Recommendation for further studies

Even though the prototype potato grader for use with Shangi potato variety appears to be most effective at grading unit speed of 4 rpm when the angle of inclination is 0^o and feed rate of 3400kghr^{-1}. It can be recommended that;

i. The machine should be re-evaluated at more grading unit speeds, feed rates and inclination angles using different variety of potato tubers.

ii. The collection tubes and trays could be padded to reduce mechanical damage of the tubers.

iii. Other sources of power such as small engines could be used to increase the flexibility of the prototype grader.

iv. More grading unit dimensions should be evaluated to optimize grading capacity vis-à-vis the cost to benefit ratio.

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APPENDICES

Appendix I: Interaction effect of grading unit speed, angle of inclination and feed rate on mechanical damage of the potato grader

Speed (Rpm)	Angle (Ø)	Feed Rate (Kg/Hr)			
		3400	**4000**	**4600**	
6	-15	3.22	3.15	3.53	
	0	4.60	3.07	3.62	
	15	3.91	3.92	5.37	
4	-15	3.02	3.54	4.72	
	0	2.65	3.07	3.50	
	15	2.26	2.22	2.75	
2	-15	2.05	2.38	2.47	
	0	2.88	3.29	3.82	
	15	1.86	1.94	2.57	3.16

Appendix II: Interaction effect of grading unit speed, angle of inclination and feed rate on grading efficiency of the potato grader

Speed (Rpm)	Angle (Ø)	Feed Rate (Kg/Hr)			
		3400.00	**4000.00**	**4600.00**	
6	-15	89.72	90.33	90.60	
	0	88.13	89.56	89.94	
	15	89.75	90.14	89.80	
4	-15	93.34	93.03	93.18	
	0	90.57	91.38	90.27	
	15	86.97	87.19	89.11	
2	-15	86.82	87.25	87.66	
	0	90.81	88.22	86.76	
	15	87.95	84.43	85.57	89.20

Appendix III: Interaction effect of grading unit speed, angle of inclination and feed rate on grading capacity of the potato grader

Speed (Rpm)	Angle (Ø)	Feed Rate (Kg/Hr)			Grand Mean
		3400.00	**4000.00**	**4600.00**	
6	-15	3218.67	3752.42	4216.00	
	0	3230.00	3764.90	4417.50	
	15	3230.00	3668.82	4154.00	
4	-15	3128.00	3529.04	3968.00	
	0	3111.00	3423.88	4030.00	
	15	2946.67	3367.56	4115.25	
2	-15	2810.67	3302.50	3699.33	
	0	2788.00	3346.89	3875.00	
	15	2825.78	3408.93	3668.33	3518.41

Appendix IV: ANOVA on Grading Capacity

	df	SS	MS	F	Significance F
Regression	3	5218694.709	1739564.903	246.1032303	1.29527E-17
Residual	23	162574.0252	7068.435879		
Total	26	5381268.735			

Appendix V: Regression coefficient of grading capacity relating to grading unit speed, angle of inclination and feed rate of the potato grader

	Coefficients	Standard Error	t Stat	P-value
Intercept	-200.5592593	138.8721914	-1.444	0.1621
Speed (Rpm)	108.7834	9.9082	10.9791	1.275E-10
Angle (Ø)	0.2956	1.3210	0.2237	0.825
Feed Rate (Kg/Hr)	0.8208	0.0330	24.8539	4.044E-18

Appendix VI: ANOVA on grading system efficiency

	df	SS	MS	F	Significance F
Regression	3	52.78828	17.5960	5.2337	0.006688234
Residual	23	77.3277	3.3620		
Total	26	130.1159			

Appendix VII: Regression coefficient of grading system efficiency relating to grading unit speed, angle of inclination and feed rate of the potato grader

	Coefficients	Standard Error	T Stat	P-Value
Intercept	87.1362	3.0287	28.770	1.545E-19
Speed (RPM)	0.6251	0.2161	2.8929	0.0082
Angle (Ø)	-0.077894	0.0288	-2.703523	0.012
Feed Rate (Kg/Hr)	-0.000108	0.000720	-0.150667	0.88

Appendix VIII: ANOVA on mechanical damage

	df	SS	MS	F	Significance F
Regression	3	8.907	2.969	6.342	0.003
Residual	23	10.768	0.468		
Total	26	19.675			

Appendix IX: Regression coefficient of mechanical damage relating to grading unit speed, angle of inclination and feed rate of the potato grader

	Coefficients	Standard Error	T - value	P-value
Intercept	-0.260	1.130	-0.230	0.820
Speed (rpm)	0.309	0.081	3.834	0.001
Angle (Ø)	-0.005	0.011	-0.441	0.663
Feed Rate (Kg/Hr)	0.001	0.000	2.032	0.054

Appendix X: Picture of Prototype Irish Potato Grader


a) Front Elevation b) Side Elevation

Appendix XI: Similarity Report

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Certificate of Plagiarism Check for Thesis

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