Expl Agric. (2005), volume 41, pp. 81–92 © *2005 Cambridge University Press*
DOI: 10.1017/S0014479704002340 *Printed in the United Kingdom*

MECHANIZATION OF POTATO GRADING ON SMALL-SCALE FARMS: A CASE STUDY FROM PERU

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(*Accepted 27 July 2004*)

SUMMARY

Potatoes are an important cash crop for small-scale producers worldwide. The move away from subsistence to commercialized farming, combined with the rapid growth in demand for processed agricultural products in developing countries, implies that small-scale farmers and researchers alike must begin to respond to these market changes and consider post-harvest treatment as a critical aspect of the potato farming system. This paper presents and assesses a low cost potato-grading machine that was designed explicitly to enable small-scale potato growers to sort tubers by size for supply to commercial processors. The results of ten experiments reveal that the machine achieves an accuracy of sort similar to commercially available graders. The machine, which uses parallel conical rollers, has the capacity to grade different tuber shapes and to adjust sorting classes, making it suitable for locations with high potato diversity. Its relatively low cost suggests that an improved and adapted version of this machine might enhance market integration of small-scale potato producers not only in Peru, but in other developing countries as well.

INTRODUCTION

In recent decades, there has been an increase in the use of processed potato (*Solanum tuberosum*) products in developing countries due to changes in lifestyle resulting from urbanization and the growing role of women in the workplace (Scott *et al.*, 2001). In Peru, as in other developing countries, potato-processing companies require a regular, reliable supply of high quality, uniformly-sized potatoes. These are increasingly being obtained from large-scale producers through contract agreements, to the detriment of small- and medium-scale potato farmers (Bernet *et al.*, 2002).

In order to sell to potato processors, and join this expanding market, small- and medium-scale farmers need to produce a high quality, standardized product and to organize into co-operatives to sell in sufficient quantities. Post-harvest treatment and mechanization to select, clean and grade tubers form a vital component in the farming system and can help to achieve increased quality and standardization of the product.

This paper describes the development and evaluation of a low-cost, flexible potato grading machine for small- to medium- scale farmers in Peru and compares it with available technology. It is hoped that such a machine could be used by potato-growing communities throughout the developing world to increase their income and productivity, by allowing farmers to achieve higher prices for a better quality product while reducing labour requirements.

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https://doi.org/10.1017/S0014479704002340 Published online by Cambridge University Press

SMALL-SCALE POTATO FARMING IN PERU

In Peru, potatoes are cultivated in the dry tropical coastal area, and in the highland sierra. They are grown and harvested throughout the year due to climatic variations between these two zones. Local harvests, especially in the Andean highlands, are highly seasonal, however, and require a large labour force, which cannot always be found in the area. This drives up the price of seasonal contracted labour and requires close supervision to ensure high quality work.

Small- and medium-scale farms (less than 3 ha) in Peru are found predominantly in the highlands and account for 85% of national production, with an average yield of 11.4 t ha^{-1} (DGPA, 2001). Over sixteen commercialized varieties of potatoes are grown in the central highlands and sold in urban marketplaces. The tubers vary in size, shape, colour and consistency, and play an important role in the Peruvian diet accounting for 13% of the calories consumed (Mendoza, 2002; FAOSTAT, 2001).

At present, there is very limited mechanization on small-scale potato farms. Tubers are sorted by hand and packed in sacks that weigh up to 130 kg. Bruising is a problem in such large sacks, making the product less desirable to processors.

Despite Peru's dependence on the nutrition provided by potatoes, consumption levels of processed potato products are low compared to other more developed countries, accounting for only 2.8% of total potato consumption in Peru, compared to 47% for the Netherlands where the potato is also a major food crop (FAOSTAT, 2001). This divergence indicates that, as Peru's consumption patterns change and its urban areas expand, the demand for processed potato products is likely to continue to grow, making this an opportune time for small-scale farmers to expand into this segment of the market (Scott *et al.*, 2001).

A potato-grading machine suitable for use on small-scale farms will help farmers to respond to these new marketing opportunities by providing the tools necessary to produce a high quality standardized product suitable for the potato processing industry.

PERFORMANCE INDICATORS FOR POTATO GRADING MACHINES

Potato-grading machines designed to work on small-scale farms in the developing world must satisfy both technical and economic requirements, as well as considering social factors for successful technology adoption. Machines must not only be suitable for use in harsh physical conditions, but they must also be profitable to the farmer. Such machines must be able to grade a wide range of tuber sizes and shapes efficiently and cost-effectively in the short and long term. To assess the physical and economic performance of grading machines, several indicators have been selected (Table 1).

CURRENT SORTING METHODS

Many systems have been developed to sort potatoes. These can be divided into three technology groups:

Mesh screen grader: This type of grader is widely used and can have multiple configurations. The system consists of a metal, plastic or rubber mesh, through which

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Table 1. Performance indicators for potato grading machines.

Technical indicators	
Rate of sort	Capacity of the machine to sort potatoes (*tubers* h^{-1})
Accuracy of sort	Capacity to correctly classify potatoes (*% correctly sorted tubers*)
Damage	Capacity to grade the potatoes without causing undue damage to the tuber (*% damaged tubers*)
Economic Indicators	
Investment	Amount of initial capital investment (*US dollars*)
Profitability	Life time profitability of the machine (*Internal rate of return*)
Social indicators	
Flexibility and usability	Ease of use and flexibility of the machine (*Qualitative evaluation*)
Transportability	Ease with which it can be transported between farms and regions (*Qualitative evaluation*)
Safety	Assessment of risk of injury by grader (*Qualitative evaluation*)

tubers smaller than the mesh size pass (Witney and McRae, 1992). A series of these meshes can be put together to provide a range of grades. Meshes are often agitated to assist the passage of potatoes (Bishop and Maunder, 1980). According to performance data, mesh screen graders are 95% accurate within a tolerance limit of 12.7 mm (Key Technologies Inc., 2003).

A mesh screen grader has also been specifically designed for small-scale farmers in developing countries. This machine (FAO–Proyecto Poscosecha, 2001) was designed in Bolivia. It consists of three screens, one on top of the other, of decreasing grades, shaken with a rocking motion. Tubers are collected and bagged from the screen at which they stop. This is a hand-operated system that is capable of sorting 900 kg h^{-1}, and it takes 3–5 people to operate.

Potato damage, such as scuffing and bruising, can be a problem in mesh screen graders especially under vertical agitation, and the system works better with spherical tubers (Witney and McRae, 1992).

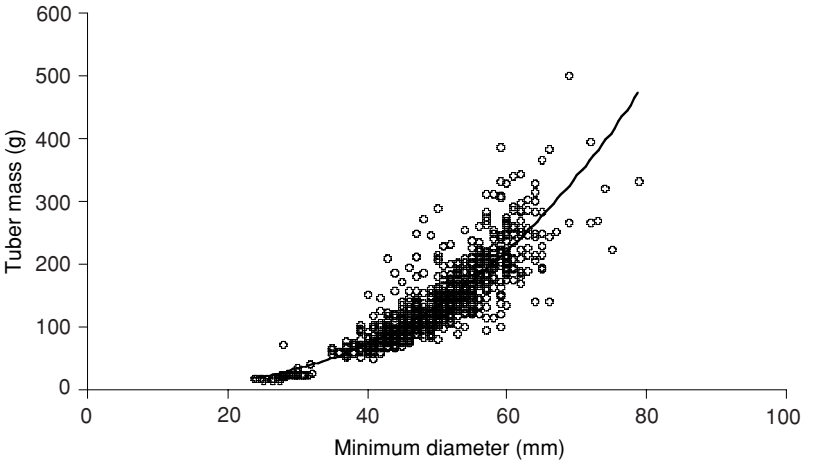
Expanding roller sorters: In this sorting method, the tubers are conveyed over a series of rollers. The space between each of these rollers is increased so that when the gap is larger than the diameter of the tuber it will fall through to the appropriate selection tray. Hutchinson and McRae (1980) measured the precision of a plain roller grader and found it to be 85–91% accurate with zero tolerance limits.

Compared to the mesh screen grader the expanding roller sorter is gentler on the potato, causing less bruising and scuffing. Rubber covered, moulded, and drop rollers are used to improve accuracy and minimise drop damage (Witney and McRae, 1992).

A few of the largest producers and processors occasionally use expanding roller sorters in Peru, but their use of this method is limited because of the relatively high cost.

High technology sorting: These methods are worth mentioning briefly, though their applications in the developing world are limited due to the high cost. Optical sorting uses digital imagery. This allows a computer model to be built for each individual tuber, allowing them to be sorted by volume, mass, shape or any other visually detectable or calculable parameter (Zhou *et al.*, 1998; Marchant *et al.*, 1990). Finger sorters use

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Variety	Equation	R^2	n
INIA Canchán	$y = 0.0022x^{2.8081}$	0.84	880
Perricholi	$y = 5.277e^{0.6381x}$	0.83	233
Peruanita	$y = 5.4627e^{0.6092x}$	0.86	203
Amarilla Tumbay	$y = 8.3501e^{0.4981x}$	0.80	1283
Diacol Capiro	$y = 4.9128e^{0.522x}$	0.96	1228

Figure 1. Chart of the relationship of minimum tuber diameter and mass for cultivar INIA Canchán. Correlation equations for other cultivars including non-adjusted R^2 values and sample sizes '*n*'.

mechanical fingers to create an electronic profile of the tuber, and a computer then classifies these tubers according to a calculable criterion such as mass, length or height. This system has been developed and commercialized in Australia by EDP Australia Pty. Ltd.

DESIGN OF A NEW FLEXIBLE POTATO GRADER

In Peru, most potatoes are currently hand-sorted according to their size. This relies on a cognitive perception of both mass and shape. A study of different potato varieties shows that there is a statistical relationship between minimum tuber diameter and mass. The results of these studies demonstrate that there is a good correlation for all the varieties studied (Figure 1). It can be concluded that a population of tubers sorted by minimum diameter will also be sorted by mass according to these relationships and variances.

The new flexible potato grader sorts by minimum diameter. It consists of two parts that can be separated to increase portability: the selection table for cleaning, selecting inferior tubers and removing stones and debris; and the grader for sorting them according to their minimum diameter (Figure 2).

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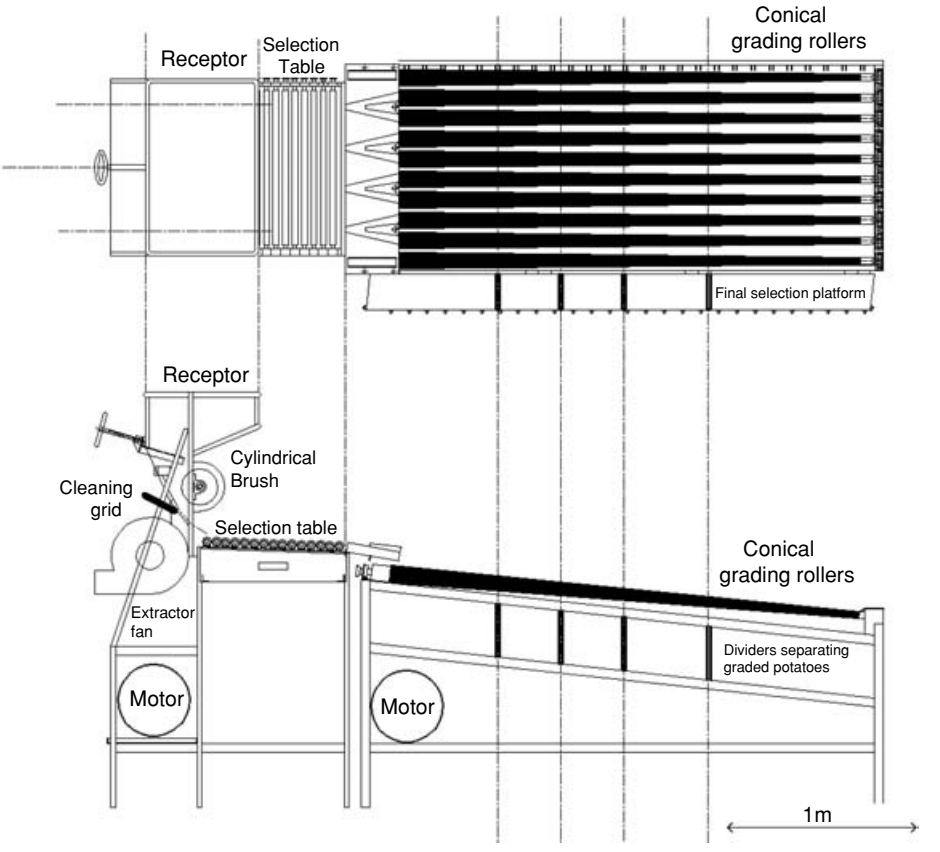


Figure 2. Top and side view schematic of the new potato grader using conical rollers.

Selection table and brushing mechanism

A 3.5 Horse Power (HP) gasoline motor is located below, and coupled via a series of belts, pulleys, chains and sprockets to enable it to power the selection table, extractor fan and cylindrical brush.

First, the tubers pass from the 123 L receptor through a channel where they move between the cleaning grid and the cylindrical brush (100 mm radius), which is turned by the motor, cleaning them as they pass. Air is drawn through the cleaning grid by a centrifugal extraction fan, which is also powered by the motor. In this way, some of the loose debris and dirt is removed from the potatoes and expelled through the cleaning grid by the extractor fan. The brush is located directly below the receptor and opposite the cleaning grid with a clearance of 60 mm. The extractor fan is located behind the cleaning grid through which it draws air.

The tubers then pass over the selection table, which consists of 15 polyvinyl chloride rollers 0.85 m long and 0.032 m in diameter, turned by the motor. The rollers are rotated so that potatoes move forward and are agitated as they pass, allowing the selector to view the tubers from several angles and to remove any that are green, insect damaged or rotten. From the selection table the potatoes pass to the grader.

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Grading and bagging mechanism

The grading mechanism is powered by a 6.5 HP gasoline motor located beneath the grader and coupled via a pulley mechanism.

The grader consists of 10 conical wooden cylinders mounted on bearings with parallel axes oriented parallel to the flow of tubers. Each cylinder is 2.67 m long, with a diameter decreasing from 300 mm, closest to the selection table, to 92 mm, furthest from the table, and is turned by the motor. Tubers pass between these cylinders until their minimum diameter exceeds the gap and they fall into the space below. Different sized potatoes fall through at different stages. There are dividers placed in the space beneath the rollers to separate and provide channels for the different grades. Dividers can be placed at any point, creating a versatile system of classification. The tubers slide down the channel between the dividers, which is covered with a foam layer approximately 7 mm thick, and designed to minimize drop damage. From the channels the tubers pass over a final selection platform and into 50 kg collection sacks, attached by clips. The operators can perform a final inspection of tubers as they pass over the final selection platform.

The machine requires four or five operators. This includes two or three people for the selection table and brushing mechanism, one of whom will load the tubers into the receptor, and the others will remove inferior tubers at the selection table. The grading and bagging mechanism requires two operators at the final selection platform to change the bags and perform any final reclassification.

PERFORMANCE ANALYSIS

In 2003, twelve field tests were carried out at the International Potato Center in Lima, and on cooperative farms in the Chillon valley. Co-operative farms are administered by 'Fovida', a local non-governmental organisation. Tests were performed with sample sizes ranging from 100 kg to over 1000 kg with three different cultivars of potato, Amarilla Tumbay, INIA Canchán and Diacol Capiro, all commonly grown in Peru. The tests were designed to establish some of the performance indicators for the potato-grading machine and to assess social factors influencing its use.

Tubers were classified into five different groups based on the standards of a new commercialization scheme and brand name known as 'Mi Papa'. These standards were developed in a participatory process among market chain actors, and they are summarized in Table 2 (Manrique, 2002).

The first field test was carried out with a sample of 920 tubers of the variety INIA Canchán. Each tuber was numbered and the minimum and maximum diameters, and mass were tabulated. These tubers were passed through the machine, and the time for the test and the classification results for each tuber were recorded. Based on this information the performance indicators were calculated. Six tests were subsequently carried out with 100 kg samples of INIA Canchán to establish whether the results were consistent. Similar tests were carried out for Amarilla Tumbay (1279 tubers) and Diacol Capiro (1216 and 1226 tubers). Finally, two trials were carried out in the field using samples of 500 kg and 1100 kg of Diacol Capiro and INIA Canchán to evaluate

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Table 2. Criteria for selection using the 'Mi Papa' commercialization scheme for three popular Peruvian potato cultivars.

	Minimum diameter		
Class	Canchán	Capiro	Amarilla Tumbay
Premium	≥ 60 mm	≥ 60 mm	> 65 mm
Large	51–59 mm	51–59 mm	56–65 mm
Standard	45–50 mm	45–50 mm	45–55 mm
Small	34–44 mm	3.4–4.4 mm	34–44 mm
Baby	26–33 mm	26–33 mm	26–33 mm

Table 3. Average accuracy information for each variety graded. Percentage classified refers to the number of tubers in each class as a percentage of all potatoes in the sample. Accuracy is shown with 0 mm and 2 mm tolerance.

Variety:	INIA Canchán			Diacol Capiro			Amarilla Tumbay		
	Percentage	Accuracy (%)		Percentage	Accuracy (%)		Percentage	Accuracy (%)	
Class	classified	0 mm	2 mm	classified	0 mm	2 mm	classified	0 mm	2 mm
Baby	0.1	100	100	0.4	15	100	0.1	100	100
Small	16	83	97	8	94	96	8	81	92
Standard	28	69	85	43	72	84	71	84	95
Large	41	85	91	28	81	93	19	61	78
Premium	15	53	69	21	73	94	2	74	85
Total	100			100			100		
Average accuracy		75.4	87.0		76.9	89.6		79.6	91.4

the grading machine as a component of the harvesting system. Local farmers were involved in the testing process and provided their perspective on the machine as its eventual end users. A separate trial was carried out with hand graders to quantify the reliability of hand grading.

RESULTS

Rates of sort for the machine ranged from 2300 to 3800 kg h^{-1}, depending on the efficiency of the workers, the continuity of the supply of tubers and whether or not the motors stalled and needed to be restarted.

Accuracy of sort was assessed by comparing the measured minimum diameter of each tuber with the range of sizes allowed in the class. Tubers that fell within this range were considered to be graded accurately. It was observed that inaccurately classified potatoes were misclassified by a small amount and to illustrate this the relatively small upper and lower tolerance bounds of 2 mm were selected. To calculate the accuracy with this tolerance the same test was used but with the class boundaries extended by 2 mm. For example, at zero tolerance the minimum diameter of the tubers in the small class were compared against a range of 34–44 mm, whereas for 2 mm tolerance it was compared to a range of 32–46 mm tolerance. The figures for accuracy of sort are shown in Table 3.

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The consistency of the first seven tests for INIA Canchán was established by using a 'two-sample test of percentage for large samples', to compare the mean values against the individual results. The second and third trial results were not considered because of external factors that influenced the tests. Of the five tests considered, four fell within the 5 % significance level ($n = 3799$, $\bar{X} = 75.3\%$, *s.d.* = 1.68%). The unexplained deviant result increased the standard deviation to 2.96%. It can therefore be concluded that the trials, although variable, showed overall statistical consistency.

The results show that there is a statistically significant variation in the accuracy of sort between different cultivars. The mean result of the tests showed a significant difference at the 5 % level between INIA Canchán ($n = 3799$, $\bar{X} = 75.3\%$, *s.e.* = 1.48%) and Amarilla Tumbay ($n = 1276$, $\bar{X} = 79.6$, *s.e.* = 0%). However, the results for INIA Canchán and Diacol Capiro were similar ($P > 13\%$).

There were significant differences ($P < 5\%$) between the mean accuracy of sort and the accuracy for each class category. The class with the smallest standard deviation was the 'large' class, which also contained the most tubers, graded with a relatively good (85%) accuracy. 'Baby' class was not considered in this test due to the small number of tubers in this category.

The majority of errors in classification were of small magnitude, so a large change in accuracy occurred between the calculated values for zero tolerance (75–80%) and ± 2 mm (87–91%). There was a tendency for borderline tubers to pass along the rollers slightly too far and fall into the size above the correct category.

The rate of external damage depended largely on the variety of potato and the harvesting conditions, but usually only amounted to slight scuffing, i.e. superficial damage, and in some cases removal of $\sim 10\%$ of the epidermis. It is estimated that slight scuffing occurred to $\leq 40\%$ of tubers for INIA Canchán and lower levels for the other cultivars tested. The brush and the conical grading rollers caused most of the damage. Severe scuffing, as described by Bouman (1996), only occurred to 0.1–0.2% of tubers and was confined to large tubers (minimum diameter > 80 mm) that became lodged behind the brush.

DISCUSSION

Rate of sort

Based on the sort rate of 2300 to 3800 kg h^{-1} and the national production average of 11.4 t ha^{-1} the machine can sort harvested tubers from 1 ha in 3–5 h. For common mid-sized tubers, an experienced human grader can sort up to 175 kg h^{-1} (24–814 kg h^{-1} for all extremes of potato sizes). It would therefore take a minimum of 13 people to sort the same number of potatoes as the grader in a given time. The machine performs at a slower rate than commercial mesh screen graders, which typically can sort 4.5 t h^{-1}.

Accuracy of sort

Shape of tuber influenced the accuracy of the selection process. Amarilla Tumbay is spherically shaped with knobbly surface contours and was sorted with the highest average accuracy. In contrast, INIA Canchán and Diacol Capiro have a smooth,

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regular surface but a very variable shape and were sorted with a lower average accuracy, suggesting that shape rather than surface texture is an important factor in accuracy of sort.

There is a significant difference between accuracy for size classes. Differences show no clear pattern although, for a single variety, differences were consistent between tests. It was observed that borderline tubers, would tend to pass along the rollers slightly too far and fall into the neighbouring category. For this reason, errors tended to be small in magnitude, and within a tolerance of 2 mm a much higher accuracy was achieved.

Compared with hand grading, the machine sorts with greater accuracy. This is demonstrated by an average accuracy of 65% for a sample of 1226 tubers of hand selected Tumbay Amarilla by four experienced hand graders. This value was measured with zero tolerance, and compares with an accuracy of 80% at zero tolerance for machine grading.

Commercially available grading machines sort with varying accuracy. Expanding roller sorters have been found to sort with an accuracy of 85–91% at zero tolerance (Hutchinson and McRae, 1980) and mesh screen graders have been found to sort with an accuracy of 95% within 12.7 mm tolerance (Key Technologies Inc., 2003). The new design is able to sort to > 99% accuracy within a tolerance of 12.7 mm, which implies a better accuracy than the mesh screen grader, and is almost as good as the expanding roller sorter.

Damage

This was mainly confined to slight scuffing of ≤ 40% of tubers. The damage could be greatly reduced by removing the brush, which is a principal cause of the problem. This would also reduce the cost of the machine. In addition, to reduce scuffing further, the conical rollers could be manufactured from a less abrasive material such as polyvinyl chloride.

In these trials no assessment was made of internal damage or bruising. The design included a 7 mm thick cushioning foam layer under the grading rollers, however, to minimise drop damage to the tubers. The use of foam cushioning has been found to significantly reduce levels of bruising due to impact (T. Van Canney, personal communication, 2004).

Very little has been published on potato damage for different grading systems. It was observed that the level of scuffing with the new system was higher than that for the expanding roller sorter. This observation was made during an unrelated trial involving an expanding roller sorter with rubber covered moulded rollers carried out by the NGO Fovida.

Investment

This prototype machine cost approximately US$ 4000 to design and build, about half the cost of the most economical commercial graders. The cost of the machine could be significantly reduced through design simplifications and the production of

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several machines. It is estimated that in this way the production cost could be reduced to US$ 2500 per machine.

Profitability

Five people are required to operate the machine in its present form. This implies that the machine can sort 2.75 times more potatoes per person per unit time than hand grading. Wages for labourers currently range from 15 to over 30 Peruvian Nuevos Soles per day (US$ 4.35–8.70 based on an exchange rage of 3.45 in December 2003). This indicates that using the machine will create a financial saving in terms of labour of US$ 38–76 for a full day of harvest. These estimates do not take into account the cost of supervision and the variability of the performance of hand sorters. Fuel costs for the machine are US$ 15.00 for the 19 L of petrol needed for a full day. Maintenance is estimated to be an additional US$ 2.25 per working day (15% of fuel costs).

Based on these estimates of savings, it would take farmers between 68 and 192 harvesting days to recover the US$ 4000 capital investment (an average of approximately 338 ha or 3858 t based on mean national production levels of 11.4 t ha^{-1}). By comparison, if the capital cost was reduced to US$ 2500 it would take farmers between 43 and 120 harvesting days to recover the capital investment (approximately 212 ha or 2421 t). For this machine to be beneficial to farmers they would need to form cooperatives so that it could be shared between farms and regions (with different harvesting times), thereby maximizing the number of harvest days possible.

Flexibility and usability

The flexibility of the machine is a major advantage of the design making it appropriate for use in countries with high potato genetic diversity such as Peru. Major advantages include:

1. Capacity to grade a wide range of potato sizes from about 20 mm to 80 mm minimum diameter.
2. Fast and easy adjustment of the sizing criteria.
3. Processors can dictate the sorting criteria that they require.
4. A large number of selection criteria can be specified within the range of gradable sizes.

The usability of the machine was discussed with farmers. Several problems were raised and some solutions to these problems were suggested. The main disadvantages of the machine include:

1. The machine seemed complex to farmers.
   - Special training would enable more efficient use and a higher level of comfort with the technology.
2. The selection table was too high for most of the workers.
   - The machine could be equipped with platforms at an appropriate height.

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3. The receptor was too high for workers to load potatoes comfortably.
   - A ramp could be attached to the machine giving easy access to the receptor.
4. Flow of potatoes was constricted at the point where the sacks attach to the collection trays because the sacks could not be changed quickly enough.
   - This will most likely improve with practice and training. It could also be resolved by redesigning the sack changing mechanism.

Most commercially available mesh screen graders and expanding roller sorters were not designed with flexibility in mind because they were not intended for farming systems with high genetic diversity.

Transportability

Transportability between nearby farms and fields in the same region was a problem. The machine has no wheels and weighs approximately 500 kg. Its dimensions (grader: 2.5×0.95 m selection table: 1.3×0.95 m) are such that 4–5 people are required to carry each section of the machine from field to field. This situation resulted in the potatoes being brought to the machine rather than the machine to the potatoes. Cost of transportation is relatively high, making the use of a vehicle cost effective only for distances great enough for the costs to be justified by the motive for moving the machine. Transportability was not a problem when using a vehicle to transport the machine long distances between regions, since both sections can, with comparatively little effort, be lifted onto a vehicle or trailer.

Safety

Guards cover most moving parts of the machine. The major safety hazard is the size of the machine, which requires one operator to climb up it in order to deposit tubers into the receptor.

CONCLUSION

The design principle of the machine using parallel conical rollers to sort tubers has shown potential as an economical method for use in rural areas of the developing world. Such a machine can improve the retail value of the crop and open the doorway for small-scale farmers to organize themselves to sell to potato processors.

Test results show that this machine can sort with an accuracy that is superior to hand sorting and comparable with other commercial grading machines. It is flexible enough to be used for the vast array of Peruvian potato cultivars and to accommodate any special sizing requirements specified by processors.

The design details of the machine can be improved upon and adequate training must be provided to farmers, taking into account their specific cultural and economic needs, including access to and cost of labour and capital. For this machine to be effective, it will be important to include ongoing extension activities to ensure proper adoption and maintenance of the machine. This machine shows potential, however, as a foundation concept that could increase product quality and the competitiveness of small-scale potato producers in the developing world.

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