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Supply and Demand of Processed Potato Products in Kenya, Rwanda, and Uganda: Variety Requirements of Processing Companies and Implications for Trait Prioritization for Breeding

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Abstract
The potato processing industry in Kenya, Rwanda, and Uganda is expanding rapidly. This study assesses the current situation and outlook of the local industrial potato processing sector and the alignment of the industry's variety requirements with the priorities set by breeders. Currently, potato processing companies in the three countries use both varieties selected locally from public international germplasm and varieties introduced by Dutch seed companies, and their suitability for processing is discussed as well. Overall, the processing industry pays high attention to traits affecting processing efficiency and consumers' acceptance while breeders, in spite of being aware of the characteristics required for processing varieties, are more focused on traits related to production and disease resistance. As the processing sector develops further, breeders will have to pay increased attention to the progressively stricter requirements of the industry, striking the right balance between farmers' and processors' variety requirements. While their opinions on the farmers' acceptability of processing varieties diverge, breeders and industry agree about the challenges represented by the limited access to quality seed and poor business linkages between value chain actors in securing the supply of varieties suitable for processing. Based on these findings, it is recommended to pay more attention to both the development of dual-purpose varieties and the strengthening of the potato value chain through the improvement of business linkages between seed producers, farmers, and processing companies.

Keywords Breeding · East Africa · Potato · Processing industry · Variety traits

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Introduction

Potato (*Solanum tuberosum* L.) is the world's third most important food crop in terms of human consumption, after wheat and rice. Per capita potato consumption continues rising, especially in Asia and Africa, due to population growth, increased urbanization, change of eating habits, and increased uptake of processed potato products such as chips (French fries) and crisps (Devaux et al. 2021). Potato is an important food and cash crop for African smallholder farmers in rural areas thereby contributing to food security in the region (Sanginga and Mbabu 2015).

East Africa is the second most important potato-producing region of the continent after North Africa, where Egypt is a major player. Over the last 20 years, annual potato production in the East Africa Community (EAC[1]) has increased from 1.6 to 3.4 million tons (t) (FAOSTAT 2018). This increase in production results more from expansion of acreage under potato rather than from increased productivity. Average yield remains under 10 t/ha, below the potential of 20–30 t/ha under smallholder conditions. This indicates that innovations and technologies such as new varieties, good agricultural practices, and use of high-quality seed have not reached the necessary threshold to increase productivity in the sub-sector (EAC 2021).

While closing the yield gap will remain at the core of breeding efforts, there is growing recognition of the impelling need to refocus them towards end-product quality traits (Dufour et al. 2021). Integrating end-user preferred traits in breeding is critical to drive the demand for new varieties (Nantongo et al. 2023). In fact, while increased productivity can contribute to improved farmers' livelihoods and incomes, farmers can only achieve these benefits if the varieties they cultivate respond not only to their needs but also possess the traits demanded by consumers and other end-users in the value chain, such as retailers and processors. The relatively poor quality of end products is a particularly common issue across improved varieties of root and tuber crops, translating into low levels of varietal adoption and its subsequent benefits (Thiele et al. 2021).

Potato is used in different end products, e.g. table/ware potatoes, chips, crisps, mashed potatoes, and seed products. Current potato breeding efforts of the International Potato Center (CIP) for East Africa focus on two market segments: potato for table consumption and for processing into chips and crisps whose market is expanding rapidly. Understanding the requirements and preferences of end-users is essential for developing more demand-driven breeding products (varieties).

This article presents the results of a study which investigated the current situation and outlook of the potato processing industry in Kenya, Rwanda, and Uganda. It also discusses the potato variety traits demanded by the processing companies in these three countries and the alignment of the breeding efforts by CIP and the national research programs with their needs and requirements. Moreover, it examines whether the traits of the varieties currently used for processing meet the requirements of both the processing industry and farmers. Finally, it describes the major

[1] The EAC is currently made up of seven Partner States: The Democratic Republic of Congo, the Republics of Burundi, Kenya, Rwanda, South Sudan, Uganda, and the United Republic of Tanzania.

challenges processing companies face in securing supply of suitable varieties for processing as well as some research and development actions to be undertaken for the selection of varieties suitable for processing. These results contribute to inform breeding programs about adjustments in the traits required in new varieties to meet the requirements of growers, processors, and consumers.

Materials and Methods

This study was conducted in Kenya, Rwanda, and Uganda. The data were collected and analysed in different stages through a mixed-methods research approach.

The first stage was an in-depth literature review. Secondary information obtained from different sources, including published and grey papers and reports, publicly available statistics, websites, and resource persons, was analysed for a better understanding of the current status of the potato sub-sector and the processing industry in the selected countries. Production and yield data were obtained from FAOSTAT while import data were from the UN COMTRADE Database (https://comtradeplus.un.org/) using HS codes 200410 and 200520 for frozen ready-cut chips and crisps, respectively.

The second stage included actor mapping and key-informant interviews with breeders, industrial processors, and fast-food chains. The study did not cover small-scale cottage-level processing because of its specific objectives. Small cottage processors in East Africa (including roadside chips and crisps makers) largely use the most available fresh tubers in the market and do not seek specific varieties with processing attributes.

The interviews took place physically or over the phone using semi-structured questionnaires that were designed specifically for the breeders and the processing industry. The two questionnaires were developed to maximize comparability of the answers of the two types of respondents. Verbal consent was obtained from each respondent before the interview.

A purposive sampling method was used to select the respondents. The breeders selected were either directors, breeding program leaders, or associate breeders working for a public national (Kachwekano Zonal Research and Development institute (KAZARDI) in Uganda, Rwanda Agriculture Board (RAB) in Rwanda, and Kenya Agricultural and Livestock Research Organization (KALRO) in Kenya) or international research centre (CIP). The sampling method of the processing industry differed among the countries. In Rwanda and Uganda, all medium- to large-scale chips and crisps processors and all fast-food chains with multiple outlets in the capital cities were sampled. Secondary information and resource persons as well as personal observations were used by the authors to list and select the processors and fast-food chains in both countries. A snowball technique during the interviews also allowed the identification of new respondents not previously known. In Kenya, no fast-food chains were selected because they mostly use imported frozen ready-cut chips. Furthermore, in this country, only large-scale processors were sampled from pre-established lists of registered processing companies. The basis for their selection was to achieve a sample representing at least 30% of the processing market share, so to allow extrapolation of data at country level.

A total of 30 interviews were conducted between April and July 2023. All seven breeders selected were interviewed. In Kenya, only three out of the eight sampled processors participated in the study; however, our target market share was largely reached as each of these companies focused on a different potato product (i.e. fresh/chilled ready-cut chips, frozen ready-cut chips, and crisps) and with the relevant market share ranging from 25 to 90%. All four processors selected in Rwanda were interviewed, while in Uganda only eight out of thirteen. None of the two fast-food chains sampled in Rwanda answered to the questionnaire, in Uganda eight out of twelve. The processing companies not interviewed were either not active anymore or not willing to participate in the study.

In the third stage, the data collected during the interviews were analysed using descriptive statistics. Also, respondents provided for each product information about their current production level, their expected future output, and their estimated market share. Based on this, the total current and future market size were estimated, accordingly. The value presented is the average of these estimates. However, estimations from industries reporting market shares lower than 10% were dropped out as considered less reliable and more subject to overestimation during the extrapolation process. Finally, the results obtained were compared with the information gathered from the literature review to assist with the study conclusions.

Results

Potato Production and Processing in Kenya, Rwanda, and Uganda

Potato is a key food and cash crop in the highlands of East Africa (Kenya, Ethiopia, Rwanda, Tanzania, and Uganda), mainly produced by smallholder farmers. The tuber crop is ranked among the top 10 strategic crops for food and income security. The smallholder production systems, however, are characterized by small land parcels between 0.25 and 5 hectares (ha) and low yields ranging from 7 to 10 t/ha (Maingi et al. 2015). The average annual per capita potato consumption in Kenya and Rwanda is higher than in East Africa and the whole African continent while it is lower in Uganda (Table 1).

In recent years, chips (French fries) and crisps have become increasingly popular in urban areas in much of East Africa driven by rapid population growth and urbanization. However, until recently, East Africa had not witnessed the emergence of large industrial processors and fast-food chains on a scale that has become common in Latin America and Asia. Instead, small informal enterprises have captured a hefty niche in these urban markets, or the processing is done "in-house" by the restaurants and hotels themselves (Scott et al. 2013). This is rapidly changing with larger investors entering the potato processing sector.

In Kenya, potato is the second most important food crop after maize and a key contributor to national food security. It is also an important source of rural income. About 90% of the potatoes are grown by smallholder farmers on average land size less than 2 ha, mainly in the highlands of the Central, Upper Eastern, and Rift Valley regions. Most produce is sold through informal marketing channels for fresh

Table 1 Average annual potato production and consumption in Africa, East Africa, and target countries for the period 2019–2021

Countries	Production (,000 t)	Harvested area (,000 ha)	Yield (t/ha)	Consumption (kg/capita/year)
Africa	28,099	1871	15.0	13.6
East Africa	5510	583	9.4	14.8
Kenya	2108	215	9.8	29.4
Rwanda	938	113	8.3	63.5
Uganda	246	40	6.1	3.8

Source: (FAOSTAT 2023)

consumption. However, consumption of processed potato has undergone tremendous growth as evidenced by the increasing number of processing industries and fast-food chains, especially in Nairobi. For instance, Abong et al. (2010a) report that city dwellers in Nairobi eat potato crisps twice a week on average, mainly as snack, and found 24 brands of crisps available in the market. According to GIZ (2016), around 12% of all potatoes produced in Kenya are used for processing primarily into fresh and frozen potato chips and potato crisps. There are over 200 companies that process potatoes in Kenya, and they can be categorized into (i) *large-scale processors* and (ii) *cottage processors* based on their processing capacity (Kaguongo et al. 2014). Unlike cottage processors, large-scale processors, who process on average more than 5 t of potatoes per day, are generally very specific in quality and standard requirements for the potatoes purchased. They buy either directly from contracted farmers or from agents who bulk potatoes from different farmers and then deliver to their premises. Besides processors, there are also franchised hotels and international fast-food chains which due to the quality of locally produced potatoes not meeting the required standards mainly import ready-made frozen chips from countries like Egypt, South Africa, and Europe. Besides ready-made frozen chips, Kenya imports crisps from various countries including South Africa, Belgium, North America, and the UK. It was noted that the imported crisps were quite expensive, in some cases costing as much as twice the cost of the local ones for the same quantity. The imports were, however, of better quality compared to local ones; they had uniform size and colour with low oil contents (Abong et al. 2010a). Kenya appears to be the East African leader in potato processing, but the lack of suitable processing varieties, low quality, and price fluctuations are major constraints faced by processing companies to respond to a market that is expanding rapidly (GIZ 2014). As a result, for instance, Abong et al. (2010a) report that 82% of shops at times of the year suffer from a scarcity of crisps supply from the suppliers. The same authors, in another study, reported that 64% of crisps processors were constrained by the unavailability of suitable varieties and emphasized that, at time of the study, the processors relied on only one potato variety suitable for processing and they needed to resort to other cultivars when this was not available (Abong et al. 2010b). They concluded recommending breeders to pay more attention to avail sufficient potato cultivars for crisping.

Rwanda is the sixth largest producer of potatoes in Africa and ranks third in East Africa, after Kenya and Ethiopia. This is significant given the small size of the country. Potato is the most important cash crop but also an important food crop with a high per capita consumption of approximately 65 kg per year. Most Rwandan potato famers are smallholders, and they store on average 13% of their harvest as seed for the subsequent planting season. They sell 22% immediately after harvest for cash and about 60% is kept for household consumption (USAID-KAVES 2015). Potato production in the main producing districts in the highlands of Rwanda (Rubavu, Musanze, Nyabihu, and Burera) was found to generate on average 57% of the gross household income per year (Muhinyuza et al. 2012). The main domestic market is the local fresh market. The potato sub-sector in the country is also constrained by a limited number of private sector actors and the low levels of public and private investment in the value chain (Lombard 2017). As of 2023, there are only two enterprises making crisps and one making frozen ready-cut chips.

Uganda is the fifth largest producer of potatoes in East Africa after Kenya, Ethiopia, Rwanda, and Tanzania. The area under production has increased steadily over the years, principally under smallholder production systems which are characterized by small farm sizes of on average 1.5 ha and a low productivity of around 6 t/ha. The little use of improved varieties and certified seed and limited industrial processing and value addition are some of the major constraints affecting the development of the potato value chain in the country (Mbowa and Mwesigye 2016). Potato processing is still at a basic scale and product diversification by the industry remains minimal, specializing in only two products: chips (75%) and crisps (25%). There are no industries producing chilled or frozen ready-cut chips. The bulk of the business is undertaken by retailers like hotels, restaurants and bars, fast-food kiosks, and roadside eateries, and they produce on demand for immediate consumption (Netherlands Enterprise Agency 2021). However, there are a few industrial crisps processors, especially in the capital city Kampala. Processing companies are generally supplied by traders who are aware of the required quality specifications, particularly issues related to variety and tuber size. According to Kajunju et al. (2021), there are three major shortfalls in supplying potatoes for processing: (i) the limited volumes of clean seed produced, (ii) inadequacies in the supply of the appropriate potato varieties, and (iii) the seasonality of production creating a supply gap. This leads, among others, to a mixture of varieties being used during processing and consequently to low quality of the final products.

Overall, the potato sub-sectors in Kenya, Rwanda, and Uganda suffer from similar challenges such as availability of and access to quality seed as well as high incidence of pests and diseases. Uncoordinated and disjointed policies as well as the lack of concerted efforts to develop varieties suitable for processing are also challenges that affect the sub-sector in these countries (Maingi et al. 2015). Notwithstanding this, the processed potato market is expected to grow substantially (Table 2). Among the East African countries lays a huge untapped market for processed potato. With an estimation of 5 to 10% potatoes currently being processed in EAC (including at cottage level) and considering that the demand for processed potato, primarily chips and crisps, is increasing rapidly and is outgrowing the supply, there is room to increase investment in the processing of potato, especially to meet the increasing demand for frozen ready-cut chips (Lombard 2017).

Table 2 Market value for chips and crisps in 2016 and its potential for growth in EAC

Current market size (US $'000)			
Kenya	Rwanda	Tanzania	Uganda
$70,000	$55,000	$45,000	$5000
Potential market size in 5 years (US $'000)			
Kenya	Rwanda	Tanzania	Uganda
$120,000	$90,000	$75,000	$7000

Source: (Lombard 2017)

Current Situation and Outlook of the Processing Industry

There is a paucity of reliable information about the size of the potato processing industry in East African countries. Most available estimations consider the whole processing sector, including the informal small-scale cottage processors who currently dominate the market. The latter, however, do not seek out varieties specifically selected for processing, but pay more attention to the availability of fresh tubers of widespread varieties with some acceptable processing traits, such as Tigoni and Shangi in Kenya, as reported by Abong et al. (2010b). This is likely to continue in the near future.

Based on the information and data collected through the surveys, we have made an attempt to assess the current size and outlook of the industrial potato processing sector in the selected countries (Table 3). In Kenya, the domestic industry currently processes annually an estimated amount of about 35,000 t of fresh tubers into 6700 t of crisps, 2100 t of fresh ready-cut chips, and 450 t of frozen ready-cut chips. This means that slightly more than 1.5% of annual national potato production undergo processing on an industrial scale.

Rwanda is estimated to produce about 1800 t of processed potato products annually, mostly fried ready-to-eat chips sold by fast-food chains. This is equal to about 3700 t fresh tuber equivalents from around 450 ha (0.4% of total land under potato).

In Uganda, there are no industries producing chilled or frozen ready-cut chips. However, there are industrial crisps processors while fast-food chains are increasingly penetrating the market, especially in the capital city Kampala. The former produce annually an estimated 120 t of crisps; the latter about 540 t of fried ready-to-eat chips. Combined, they process annually about 1600 t of fresh tubers from around 260 ha of land under potato (about 0.6% of national potato acreage).

Looking ahead, respondents perceive a beaming future for the potato processing industry in East Africa. As shown in Table 4, the average projected growth of domestic production for the different processed products and countries over the next 10-year period ranges between 42 and 2500% (i.e. 25-fold the present volumes). This would result in a total production of chips and crisps in the three countries of over 35,000 t annually (about 3.5 times the present estimated volume), with especially sizeable production projected in Kenya. It is expected that the booming demand for processed potato products would be met either by the entry of more players in the market (Uganda) or through a consolidation of the sector with fewer larger players (Kenya and Rwanda). This would represent a continuation of the trends observed in these countries in the last decade.

Table 3 Estimates of current domestic production of processed potato products, fresh tuber equivalents, and land requirement

Country	Product	Actor	Estimated average quantity produced in 2020–2021 (t/year)	Fresh tuber equivalents (t/year)[1]	Average yield 2019–2021 (t/ha)[2]	Estimated corresponding land allocation (ha)	Share of current potato acreage
Kenya	Frozen ready-cut chips	Processors	444	889	9.8	91	0.05%
	Fresh/chilled ready-cut chips	Processors	2140	4280	9.8	437	0.22%
	Crisps	Processors	6667	26,667	9.8	2721	1.39%
	Country total		**9251**	**31,836**		**3249**	**1.66%**
Rwanda	Frozen ready-cut chips	Processors	2	4	8.3	0.5	0.0004%
	Fried ready-to-eat chips[3]	Fast-food chains	1775	3550	8.3	428	0.39%
	Crisps	Processors	47	188	8.3	23	0.02%
	Country total		**1824**	**3742**		**451.5**	**0.41%**
Uganda	Fried ready-to-eat chips	Fast-food chains	542	1084	6.1	178	0.44%
	Crisps	Processors	122	488	6.1	80	0.20%
	Country total		**664**	**1572**		**258**	**0.64%**

[1]Conversion rates of fresh tubers (i.e., ratio between raw material and final product) were calculated as 4 for crisps and 2 for ready-cut chips and fried chips

[2]FAOSTAT 2023

[3]All fast-food chains in Rwanda refused to be part of the survey. Therefore, for these actors, the amount of processed product was estimated by adjusting figures from Uganda based on national per capita potato consumption (FAOSTAT) and urban population (World Bank) ratios

Table 4 Past 10-year growth rate and future 10-year projections of domestic production of processed potato products, fresh tuber equivalents, and land requirement

Country	Product	Estimated increase in production over the last 10 years	Current estimated production (t/year)	Estimated increase in production over the next 10 years	Estimated production in 10 years (t/year)	Fresh tuber equivalents (t/year)	Estimated corresponding land allocation (ha)[1]	Share of current potato acreage	Increased future demand mostly met through…
Kenya	Frozen ready-cut chips	∞	444	2500%	11,556	23,111	2358	1.2%	Sector consolidation
	Fresh/chilled ready-cut chips	89%	2140	100%	4280	8560	873	0.4%	More players
	Crisps	N/A	6667	159%	17,267	69,067	7048	3.6%	Sector consolidation
Rwanda	Frozen ready-cut chips	∞	2	661%	15	30	4	0.003%	N/A
	Fried ready-to-eat chips[2]	N/A	1775	42%	2521	5042	607	0.55%	N/A
	Crisps	681%	47	1927%	950	3801	458	0.4%	Sector consolidation
Uganda	Fried ready-to-eat chips	118%	542	42%	770	1539	252	0.6%	More players
	Crisps	377%	122	132%	283	1132	186	0.5%	More players
Total			**11,739**		**37,642**	**112,282**	**11,786**	**4.8%**	

[1]Calculations based on average yields of 9.8 t/ha in Kenya, 8.3 t/ha in Rwanda, and 6.1 t/ha in Uganda

[2]All fast-food chains in Rwanda refused to be part of the survey. Therefore, for these actors, the 10-year projections are estimated using projected figures from fast-food chains in Uganda

In order to produce such volumes, the industry would need to process over 110,000 t of fresh tubers to be harvested from almost 12,000 ha (assuming no increase in farm yield). While this would represent a spectacular increment from the 4000 ha currently supplying the processing industry (see Table 3), this acreage would still represent a very limited share (4.8%) of the total area currently allocated to potato production in these countries (ranging from about 1% in Rwanda and Uganda to 5.2% in Kenya).

The level of imports of both processed products in East Africa (and Africa at large) is still limited in both absolute and relative terms (3400 t of crips per year corresponding to 19% of Africa's total, 11,000 t of frozen ready-cut chips corresponding to about 12% of Africa's total). Among East African countries, the main importers are Mozambique, Zambia, and Zimbabwe for crisps and Mauritius, Zambia, and Kenya for frozen ready-cut chips. Despite our focus countries not being among the major importers of processed potato products, they show a significant growth of imports ranging from 9 to 41% over the last 20 years (Table 5). Considering that they are also responsible for about 60% of potato production in East Africa, they are the countries in the region that offer the largest opportunities for import substitution.

Processing Industry's Preferences for Key Traits of Potato Varieties and Their Alignment with Breeders' Views

The representatives of potato processing companies and breeders indicated the importance of key traits for processing on a 5-point Likert scale, with 1 indicating a trait considered not important at all and 5 a very important trait. Figure 1 shows in decreasing order of importance the processing industry's views about these traits and compares them with the breeders' views. The latter were consistent across countries and final products (chips vs crisps). Out of the ten proposed traits, the industry gave the highest importance to frying colour, size of tubers, and storability followed by shape and oil absorption rate. The frying colour should be yellowish to golden

Table 5 Average import volume of potato crisps and frozen ready-cut potato chips in 2020–2021 HS 200410

	Potato crisps			Frozen ready-cut chips		
	Volume (t/year)	Relative share	Average annual growth rate 2002–2021	Volume (t/year)	Relative share	Average annual growth rate 2002–2021
World	854,580	–	6%	7,338,443	–	7%
Africa	18,274	2% of World	8%	95,569	1% of World	17%
East Africa	3413	19% of Africa	10%	11,211	12% of Africa	15%
Kenya	42	1% of East Africa	9%	1523	14% of East Africa	37%
Rwanda	58	2% of East Africa	41%	21	0.2% of East Africa	31%
Uganda	144	4% of East Africa	15%	438	4% of East Africa	17%

Note: (own calculation based on COMTRADE data)

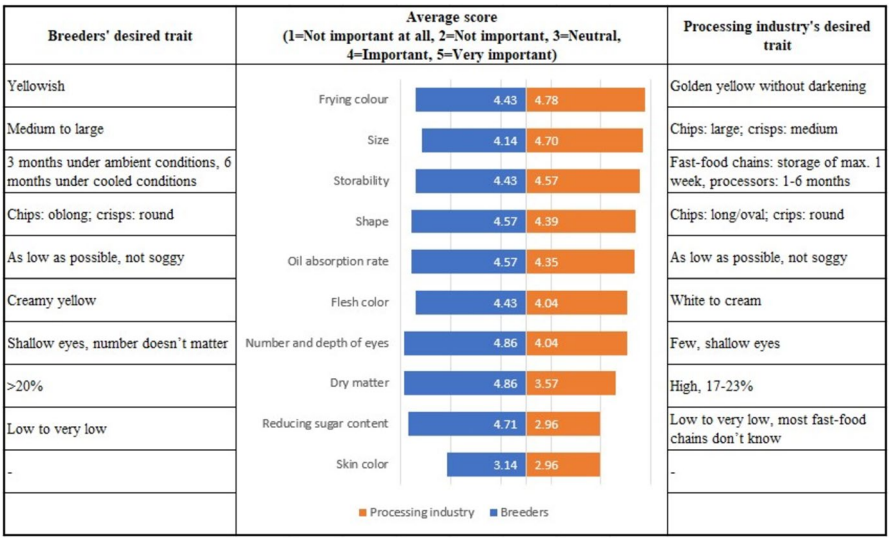


Fig. 1 Evaluation of desired traits for potato processing variety requirements by the processing industry compared to the breeders in Kenya, Rwanda, and Uganda

yellow without darkening which is mainly caused by reducing sugars. Trait differentiation between tubers for chips and crisps is more systematic among the industry compared to the breeders who highlighted this only a few times. Chips processors and fast-food chains are looking for long/oval potatoes while crisps processors are looking for round potatoes. Also, breeders in the three countries mentioned tuber shape, oblong for chips and round for crisps, as an important trait. According to them, the size is important as well and should be medium to large, but the industry is generally more precise concerning the size required for the two processed products (45–60 mm diameter for crips, 80–120 mm length for chips).

Tuber storability is important for both breeders and industry, with breeders recommending at least 3 months of storage in ambient conditions without sprouting and up to 6 months in cold storage. The processors indicate a required storability of 1 to 6 months with preference for more than 3 months. For the fast-food chains, storability is less important because they buy potatoes when needed and store them only for a few days.

Oil absorption rate is important for both the breeders and industry and should be as low as possible because it affects processing costs and product quality.

There is consensus regarding the importance of flesh colour between breeders and industry with a preference for light yellow. One breeder, however, made a distinction between the required flesh colour for chips (creamy yellow) and crisps (white). Overall, both breeders and industry assign the least importance to skin colour.

Regarding the number and depth of the eyes, the shallowness of the eyes is important for both breeders and industry. However, the processing industry prefers tubers with few eyes while the number of the eyes is not considered an important trait by the breeders.

Dry matter is an important criterium for all breeders recommending a percentage above 20% up to 24%, but with no differentiation between chips and crisps. Knowledge about dry matter varies among industry and countries. No fast-food chains indicated specific dry matter content requirements; only the processors referred to it. All processors in Kenya were able to indicate a specific value for the desired percentage of dry matter ranging from 17 to 23%, in Uganda and Rwanda only one. Reducing sugar content is another key criterium that must be as low as possible. No specific values, however, were mentioned by the breeders. One of them in Kenya, however, mentioned the existence of specific standards for reducing sugar content. On the industry side, reducing sugar content does not appear to be a high priority.

Although breeders are generally aware of the traits required for processing varieties, they indicate to consider processing qualities of potato varieties mostly at later stages of the breeding process (during clonal selection), with only a few considering them at an earlier stage (during parental selection). Thus, breeders seem to prioritize traits related to primary production over the ones affecting processing efficiency and consumers' acceptance of processed products. The main traits used when selecting potato varieties are generally productivity and disease resistance.

Availability and Use of Potato Varieties for Processing

Our findings show that the processing industry in Kenya, Rwanda, and Uganda currently uses both varieties selected locally from CIP germplasm and varieties introduced by Dutch seed companies. However, there is some divergence between the varieties the processing industry in these countries actually uses and the varieties of what breeders think they use (Table 6). Overall, in Kenya and Rwanda, three out of five varieties cited by either the industry or breeders coincide. In Uganda, it is only three out of eight varieties.

Breeders confirmed that the processing industry in each country is looking for varieties selected for their processing traits; however, most of the varieties mentioned by them in Rwanda (Gikungu, Kinigi, Kirundo, and NAROPOT 4/Rwangume) and Uganda (KACHPOT 1, Kinigi, NAKPOT 5, and NAROPOT 4/Rwangume) were selected from CIP germplasm. Conversely, in Kenya, out of the four main varieties mentioned by the breeders (namely Dutch Robijn, Markies, Shangi, and Tigoni), only Shangi and Tigoni were selected from CIP material while most of the others were introduced by Dutch seed companies. Out of the varieties introduced by Dutch seed companies and actually used by processing industries in Kenya, such as Challenger and Markies, only Markies was also mentioned by the breeders.

In Kenya, three out of the four varieties reported to be used by the processing industry (Challenger, Dutch Robijn, and Markies) have specific processing traits and are of foreign origin. This is the case for only one of three varieties in Rwanda (Taurus) and two out of eight varieties in Uganda (Markies and Taurus). Although most processing companies are aware of processing varieties, they often do not seek out varieties specifically selected for processing. Rather, they pay more attention to the availability of fresh tubers of widespread varieties with some acceptable processing traits. This is particularly the case in Rwanda and Uganda where the industry

Table 6 Main varieties used by the processing industry in Kenya, Rwanda, and Uganda, as indicated by breeders and the processing industry

Variety	Country					
	Kenya		Rwanda		Uganda	
	Breeders	Industry	Breeders	Industry	Breeders	Industry
Challenger*		√				
Dutch Robijn*	√	√				
Gikungu**			√			
KACHPOT 1**					√	√
Kinigi**			√	√	√	√
Kirundo**			√			
Markies*	√	√				√
NAKPOT 5**					√	
NAROPOT 4/Rwangume**			√	√	√	√
Rutuku**						√
Shangi**	√	√				√
Taurus*			√	√		√
Tigoni**	√					

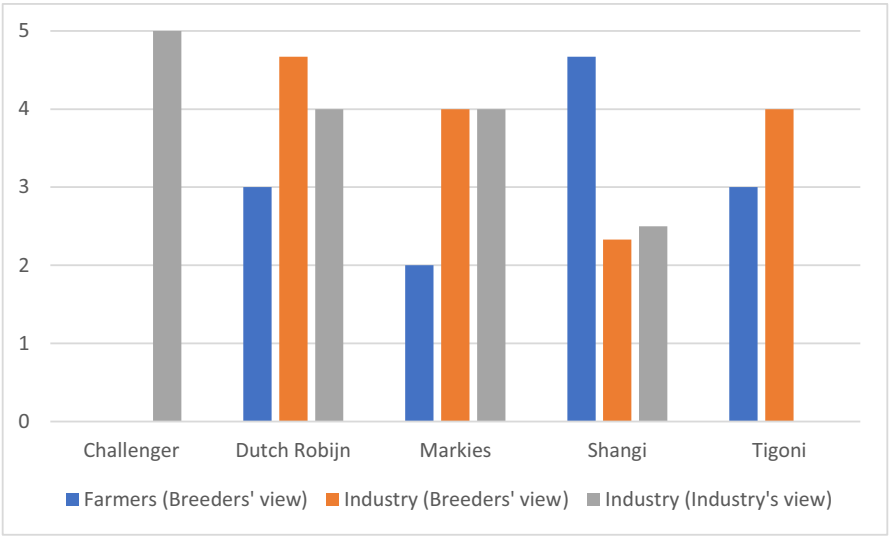
*Dutch variety

**Selected from CIP germplasm

mainly reported the use of Kinigi and NAROPOT 4/Rwangume. Both varieties are well appreciated by farmers and widely grown in these countries because of their robustness under local conditions. Initially selected from CIP germplasm for their adaptation and good production characteristics including disease resistance (e.g., to late blight), these varieties also showed acceptable traits for processing. Therefore, they are often referred to as dual-purpose varieties.

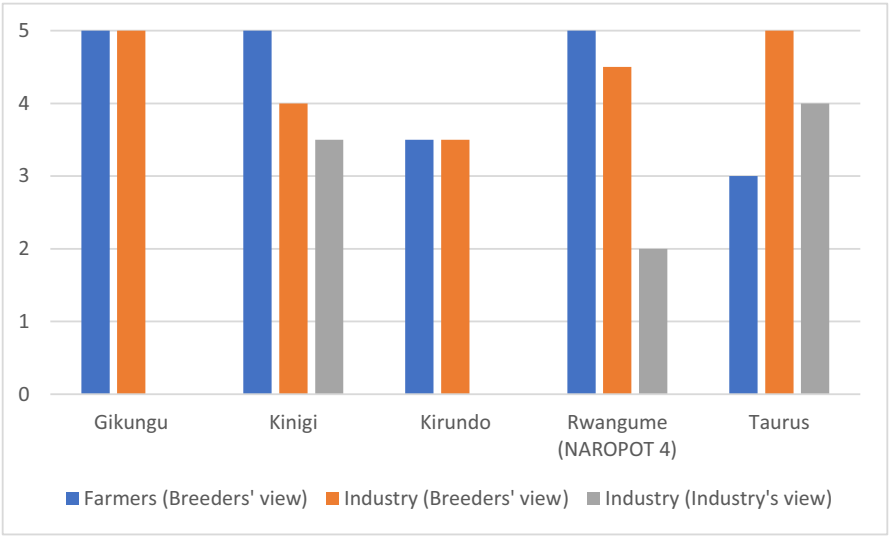
Figures 2, 3, and 4 summarize the breeders' points of view on how well the characteristics of the assumed most common varieties used by the industry meet the farmers' and industry's requirements in Kenya, Rwanda, and Uganda, respectively, and compare them with the industry's point of view on the suitability for processing of the varieties the latter actually use. For some varieties, the breeders' and industry's perceptions about processability match quite well. This is the case for Dutch Robijn, Markies, and Shangi in Kenya; Kinigi and Taurus in Rwanda; and KACHPOT 1 and NAROPOT 4/Rwangume in Uganda. For NAROPOT 4/Rwangume in Rwanda and Kinigi in Uganda, the breeders' and industry's perceptions do not match well.

Processing industries in Kenya, where the sector is in a more advanced stage of development, are more prone to seek Dutch processing varieties, such as Markies, Challenger, and Dutch Robijn. The breeders confirmed that these varieties are well perceived by the processing industry mainly due to their shape, high dry matter, low reducing sugar content, and overall good frying qualities, but indicated that they have a lower acceptance by farmers due to their susceptibility to late blight and other reasons. This explains the reason why several industries in Kenya still largely procure varieties



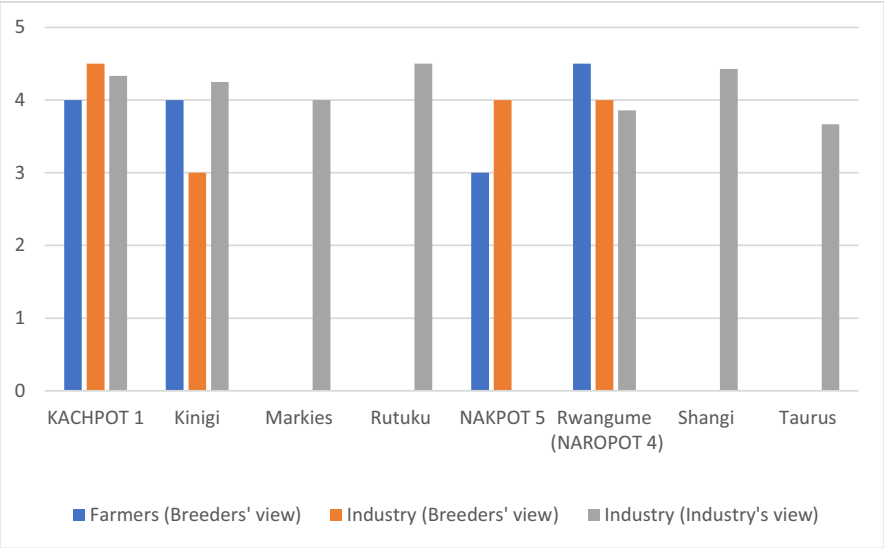
Y-axis label: 0 = I do not know, 1 = very poorly, 2 = poorly, 3 = fair, 4 = well, 5 = very well

Fig. 2 Breeders' perception of farmers' and industry's preferences of assumed most common varieties used by processing companies in Kenya compared to the industry's view on the varieties the latter actually use



Y-axis label: 0 = I do not know, 1 = very poorly, 2 = poorly, 3 = fair, 4 = well, 5 = very well

Fig. 3 Breeders' perception of farmers' and industry's preferences of assumed most common varieties used by processing companies in Rwanda compared to the industry's view on the varieties the latter actually use



Y-axis label: 0 = I do not know, 1 = very poorly, 2 = poorly, 3 = fair, 4 = well, 5 = very well

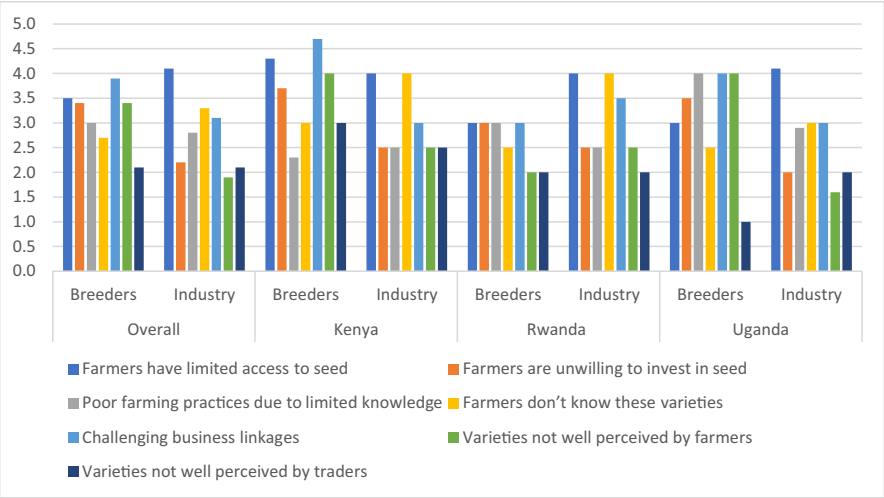
Fig. 4 Breeders' perception of farmers' and industry's preferences of assumed most common varieties used by processing companies in Uganda compared to the industry's view on the varieties the latter actually use

selected from CIP material such as Shangi, which is widely grown, and possesses those critical traits required by farmers, such as early maturity and short dormancy. Breeders, however, indicate that Shangi meets poorly the industry's requirements and preferences because of deeper eyes. This is confirmed by the processing industry in the country itself (Fig. 2). This variety, however, is well accepted by the processing industry in Uganda. In the latter, the industry seems to value all the varieties it uses (Fig. 4).

Breeders in Rwanda indicated that Gikungu, Kinigi, and NAROPOT 4/Rwangume meet farmers' and industry's requirements and preferences well (Fig. 3). However, the processing industry in the country actually perceives Kinigi and especially NAROPOT 4/Rwangume less positively than breeders think they do. Kinigi and NAROPOT 4/Rwangume are also less appreciated by the processing industry in Rwanda than in Uganda. The main limitation of Kinigi in Rwanda was reported being its high number of deeper eyes.

Major Challenges Faced by Processing Companies in Securing Supply of Suitable Varieties for Processing

The difficulty to strike the right balance between farmers' and processors' requirements is also reflected by the different perception of breeders and industry on the main challenges faced by the latter in securing consistent supply of suitable processing varieties. Figure 5 shows the perception of processing companies about the major challenges they face in securing supply of suitable processing varieties and compares it with the



Y-axis label: 0 = I do not know, 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree

Fig. 5 Major challenges faced by the processing industry in Kenya, Rwanda, and Uganda in securing supply of suitable varieties as indicated by breeders and processing companies

breeders' point of view. While both actors agree about the challenge represented by the limited access to quality seed and poor business linkages between producers and processors, their opinions on the farmers' acceptability of processing varieties diverge. Breeders indicate the relatively poor adaptability and agronomic performance of Dutch varieties. However, the industry seems less aware of or places less importance to the negative perceptions that many producers have about them.

Research and Development Actions for the Selection of Varieties Suitable for Processing

Most of the breeders interviewed prioritized traits valued by farmers (mainly related to production and fresh market requirements) and considered the processing traits only at later stages of the breeding process (during clonal selection). However, a few of them indicated to consider processing traits at an earlier stage (during parental selection). Breeders' interaction and collaboration with processors and fast-food chains in Kenya, Rwanda, and Uganda so far mainly consisted of the evaluation and analysis of tuber samples for assessing processing traits such as reducing sugar content, oil absorption rate, and frying colour. Some breeders indicated the interest in having more frequent interactions, and more exchange of ideas with the processing industry, for better knowledge sharing and to make the breeding programs more responsive to the requirements of the industry. However, they pointed out the high costs of establishing and maintaining these collaborations (often including seed costs required for demonstration trials), which might limit them. According to one of the breeders, breeders' rights and variety protection would also imply formal agreements for this type of collaboration. Only

six processing companies interviewed (26% of the total sample—two in Kenya, one in Rwanda, three in Uganda) had ever been involved in participatory research programs for selecting varieties suitable for processing. All fast-food chains and processors interviewed, however, indicated a strong interest in being involved in such programs.

Finally, it is worth noticing that breeders did not have a strong opinion about the need for more potato varieties suitable for processing. Some of them indicated that varieties are already available and the issues around seed systems and value chain development should be rather prioritized.

Discussion

Despite some admitted limitations in our study findings due to the small sample size, we can confidently assume that industrial-level processing of potato in Kenya, Rwanda, and Uganda is still limited although it is growing at a rapid pace. This growth is expected to continue in the future. With the development of the sector, remarkable immediate opportunities exist for the development of a strong local supply chain for the processing industry contributing to import substitution. In the longer term, following the expected modernization and consolidation of the sector, more established processors will participate in the business responding better to high-value market demand than the informal cottage-level processors. It is expected that the former will likely replace table varieties (currently mostly procured in local markets) with processing varieties. This represents both an opportunity and a challenge for public breeding programs which, in alignment with national policies, will have to keep the focus on smallholder farmers' needs and, therefore, prioritize yield, disease resistance, and other production-related traits like drought and heat resistance, while meeting the progressively stricter requirements of a sector in rapid expansion.

The points of view of the processing industry and the breeders in Kenya, Rwanda, and Uganda on the priority traits for processing varieties are overall well aligned with some divergence between the two groups. The industry in the three countries considers frying colour, size, storability, shape, oil absorption rate, flesh colour, and number and depth of the eyes as important to very important traits of suitable varieties for processing. A white to cream flesh colour, a golden yellow frying colour, and a crunchiness due to a low oil absorption are needed to make the final product, both chips and crisps, visually and organoleptically attractive to the consumer. Also, a lower number and depth of the eyes is expected to reduce waste and increase productivity during processing. Regarding the shape and size of tubers, the industry pointed out a clear distinction between chips and crisps: tubers to be processed into chips should be long/oval and large, those to be processed into crips should be round and medium sized. Concerning storability, processing industries can store potatoes for up to 6 months and thus require tubers that maintain their adequate processing characteristics during that period. Conversely, fast-food chains keep their potato stored for maximum 1 week and, therefore, the reason why they deem storability as an important trait is probably

related to the health status of the tubers and not to their characteristic of being able to be stored for a long time.

Dry matter is considered of less importance by the processing industry in Uganda (3.06 on a 0–5 scale), while the industry in Kenya (5.00) and Rwanda (4.50) is giving more attention to this quality requirement. Also, the importance of reducing sugar content differs between the three countries. Processing companies in Kenya (4.67) consider this trait more important than those in Rwanda (3.50) and Uganda (2.50). This can be explained by the fact that the potato processing industry is still infant in Rwanda and Uganda. Skin colour is only used as a way to identify the right variety, which is consistent with findings of Abong et al. (2010b). Skin is peeled off and thrown away during processing. Therefore, this trait is not seen as important by the processing industry in the three countries.

By comparing priorities expressed by breeders and the industry, the former give a relatively higher attention to the number and depth of the eyes although, unlike processors, they believe that the number of eyes is irrelevant if they are shallow. They also pay much more attention to dry matter and reducing sugar content compared to the processing industry. Both are undoubtedly important factors when considering the physicochemical aspects of potato processing. However, the importance of dry matter and reducing sugar content for the processing industry differs between the three countries, and it likely reflects differences in their stage of development. It should also be noticed that frying colour is strictly linked to reducing sugar content and, therefore, the issue here is likely mostly related to breeders looking at the root cause of the problem and the industry, especially in Rwanda and Uganda, more at the resulting end product. On the other hand, the findings suggest that breeders should pay more attention to the size and storability of the tubers.

Overall, breeders, unlike the industry, indicate to pay more attention to traits related to primary production than to the ones affecting processing efficiency and the consumers' acceptance of processed products. Accordingly, priority traits used when selecting potato varieties are productivity and disease resistance. This might explain why, although breeders are generally aware of the traits required for processing varieties, processing qualities are mostly considered only at the end of the selection process.

This study shows that the processing industry in Kenya, Rwanda, and Uganda currently uses both CIP varieties (Shangi in Kenya, Kinigi and NAROPOT 4/Rwangume in Rwanda, and KACHPOT 1, Kinigi, Rutuku, NAROPOT 4/Rwangume, and Shangi in Uganda) and varieties introduced by Dutch companies (Challenger and Markies in Kenya, Taurus in Rwanda, and Markies and Taurus in Uganda). Their main qualities are their flesh/frying colour, size, shape, dry matter, oil absorption rate, processing quality, and taste as well as their overall productivity in processing. The number of varieties actually used by the processing industry in the three countries, however, is much below the available number of varieties suitable for processing into chips and crisps according to the respective national variety catalogues: 4 out of 44 varieties in Kenya and 7 out of 15 in Uganda.

The Dutch varieties are popular among the processing industry in Kenya and to a lesser extent in Rwanda and Uganda. This indicates the different levels of development of the potato processing industry in the three countries. Challenger, Dutch

Robijn, and Markies are varieties that respond well to the Kenyan industry's needs; Shangi, however, is not well appreciated among the processing companies in the country, especially the large-scale industry, but remains popular among the cottage industries (World Bank Group 2020). This observation is in line with previous studies reporting that Dutch Robijn is a popular variety among the large-scale industries due to its good storability and high dry matter content while Shangi is difficult to store and leads to high losses during processing because of deep eyes as well as lower quality of processed products (Kaguongo et al. 2014). Also in Rwanda, the Dutch variety Taurus responds better to the industry's needs compared to the CIP varieties Kinigi and NAROPOT 4/Rwangume. Previous studies reported as well that Taurus is among the best varieties to produce crisps (Rukundo et al. 2019). In Uganda, however, both CIP and Dutch varieties are popular among the processing industry, and they respond well to its needs.

Breeders in Kenya and Rwanda are quite well familiar with the varieties used by the processing industry in their country. This, however, is not the case in Uganda and especially for those varieties coming from outside the national breeding program. A possible explanation is that the collaboration between the public breeding program and the processing industry is more intense in Kenya and Rwanda compared to Uganda. The breeders in the region also confirm that the Dutch varieties used by the processing industry, such as Markies and Taurus, generally do not meet well the farmers' needs. This is in accordance with Maingi et al. (2015), Kaguongo et al. (2014), and Rukundo et al. (2019) who reported that Dutch Robijn is a low yielding variety susceptible to pests and diseases and that the cultivation of Dutch varieties requires additional inputs including agro-chemicals to achieve higher yields leading to negative implications on the cost of production and lower crop sustainability. The breeders, however, believe that CIP varieties like Gikungu, KACHPOT 1, Kinigi, NAROPOT 4/Rwangume, and Shangi meet farmers' needs well due to their tolerance to diseases, high yield, skin/flesh colour, and high fresh market demand. Kinigi, NAROPOT 4/Rwangume, and Shangi are indeed varieties widely adopted by farmers in the region. Kinigi is robust, has good yielding, and produces big tubers (Mbowa and Mwesigye 2016; PotatoPro 2018). NAROPOT 4/Rwangume produces big tubers, has a good taste, and does not become soggy when cooked (Kaguongo et al. 2008; Mbowa and Mwesigye 2016). Shangi is very popular due to its quick maturing, multipurpose, and short dormancy characteristics (Jerotich 2022).

In all three countries, the varieties selected from CIP germplasm and reported as widely used for processing were obtained from crossings made by CIP breeders in the '80s and early '90s of the last century and then tested and selected later with national potato programs. This demonstrates the long process required for the selection, release, and adoption of new potato varieties. In a review of varietal change in roots, tubers, and bananas by Thiele et al. (2021), it is mentioned that a focus on disease resistance is necessary, but entrenched consumption preferences are potentially major constraints to adoption. Also, in the case of potato, a new variety requires many years, around 20 years, before being adopted. This is especially the case for Rwanda, where all varieties suitable for processing but not yet widely grown in the country were released in 2019 and 2020. One contributing factor mentioned for high varietal age in potato in Rwanda is also dis-adoption of more modern varieties

following the genocide in Rwanda, as the collapse of the formal seed system and destruction of key research centres impeded new releases (Labarta 2015).

There is some disagreement between breeders and the processing industry on what are the main challenges faced by the latter for procuring suitable varieties in quality and quantity. Breeders believe that the main challenge faced by the processing industry is the challenging business relationships between farmers and processing companies. The latter is also observed in a study about variety preference among potato farmers in Kenya which indicates that processing quality is at the bottom of farmers' variety choice criteria (Kwambai et al. 2024). The industry, however, considers this as much less challenging. In its view, farmers' limited access to seed is by far the main challenge in procurement. Also, breeders consider the latter as a major challenge, together with farmers' unwillingness to invest in seed which is, however, not considered at all as challenging by the processing industry. Furthermore, the fact that processing varieties are not well perceived by farmers is not considered a major challenge by the industry which focuses on its own specific processing requirements. Finally, both breeders and processing companies consider farmers' lack of knowledge on good agricultural practice and on available processing varieties as less challenging.

Survey results indicate that there is much room for improving the interaction and exchange of ideas between breeders and the processing industry. The change of paradigm, like currently in Kenya, by increased involvement of the processing industry in product profiling and the selection process along the breeding pipeline, might allow to integrate as much as possible processing quality traits while keeping the focus on smallholder farmers' needs. Indeed, in alignment with national policies, breeders will have to keep prioritizing yield, disease resistance, and other production-related traits like drought and heat resistance. This is because potato is of strategic importance for Kenya, Rwanda, and Uganda where it is a key staple and cash crop, therefore contributing to the national food and nutrition security, poverty reduction, and household resilience, especially in rural areas.

Conclusion

According to the literature and results from this study, industrial-level processing of potato in Kenya, Rwanda, and Uganda is still limited but growing at a rapid pace. Demand for processed potatoes, primarily chips and crisps, is increasing rapidly in the three countries and it is outgrowing the supply. Kenya appears to be the leading country in potato processing in East Africa. There is thus room for increased investment in potato processing. Although these countries are not among the main importers of processed potato products in East Africa, they are among those that offer better opportunities for the development of a strong local supply chain for the processing industry contributing to import substitution.

The processing industry in Kenya, Rwanda, and Uganda pays overall high attention to traits affecting processing efficiency and consumers' acceptance while breeders seem to consider these processing features as secondary evaluation criteria. This might explain why, although the latter are generally aware of the traits required for processing varieties, processing qualities are mostly considered only at the end of

the variety selection process. Given the industry's strong emphasis on the differentiated traits of the fresh tubers (for both size and shape) required for ready-cut chips and crips, consideration should be given to view them as two different processing market segments for East Africa and therefore develop distinct traits for each potato product. Overall, more attention seems required for developing varieties with proper size and storability characteristics.

This study also shows that the processing industry in Kenya, Rwanda, and Uganda currently uses both varieties selected locally from CIP germplasm and varieties introduced by Dutch seed companies. Their main quality traits are their flesh/frying colour, dry matter, and high productivity during processing. Dutch varieties respond better to the processing industry's needs, but they are less appreciated by farmers because of various reasons, including their susceptibility to late blight. Some varieties selected locally from CIP germplasm, such as Kinigi and NAROPOT 4/Rwangume, in Rwanda and Uganda, however, are widely used by farmers due to their robustness under local conditions and are also used for processing. Moreover, they are quite well appreciated by the processing industry and can thus be considered dual-purpose varieties. Eventually, widespread adoption of a variety largely depends on its ability to meet both industry's requirements and farmers' needs (e.g., late blight resistance). Defining both traits valued by farmers and those required by the processing industry should allow to weigh and score them at the different breeding and selection stages. Starting an exchange with processing companies earlier in the breeding cycle would also allow breeders to improve their knowledge of the processing industry requirements and trends. As the processing sector develops further, the development by breeding programs of dual-purpose varieties responding to food security priorities while presenting good processing qualities could be an alternative to better position new potato varieties with traits responding to farmers' needs and the fresh potato market segment, which is still—and will remain in the foreseeable future—the most important in East Africa, as well as addressing the requirements of the expanding potato processing market segment. Besides the need to develop suitable varieties for processing, timely sourcing these varieties in quality and quantity is a challenge as well, mainly because of the farmers' limited access to good quality seed, as indicated by both the processing industry and breeders. In sub-Saharan Africa, there are plenty of examples of outperforming varieties (not limited to potato) that have been released but not extensively adopted because of not being widely distributed and, as a matter of fact, the vast majority of farmers do not have access to new varieties that are being introduced. Accordingly, availability of and access to healthy and affordable seed is a critical determinant of farmers' decisions on variety choice. Furthermore, market demand features as a primary determinant of variety choice among farmers (Kwambai et al. 2024). There is an opportunity for the industry in East Africa to play a more prominent role to tackle these bottlenecks. First, large-scale potato processing companies can significantly drive the adoption of improved potato varieties by creating a stable demand for high-quality tubers tailored to processing needs. By offering contracts and premium prices for these varieties, and by investing in farmer training and collaboration with agricultural extension services, processors can incentivize farmers to adopt these varieties. Additionally, the industry's investment in supply chain infrastructure and public-private partnerships can enhance the availability, access, and quality of improved potato seeds, thus

facilitating broader varietal adoption and faster turnover across the region. This would translate into a strengthening of the formal seed system. However, all potato varieties that have been introduced through the formal seed system have typically made their way to the informal system, which is and will remain the main source of seed for years to come. A stronger mechanism could be put in place for the two systems to coexist to ensure regular access to quality seed through a combination of seed merchants and farmer-to-farmer seed exchange. In conclusion, the development of dual-purpose varieties responding to the requirements and preferences of both farmers and processors is a necessary but not sufficient condition to support the rapid development of the potato processing sector in East Africa. This should be coupled with a concerted effort to the strengthening of the potato value chain through improved coordination and business linkages among seed producers, farmers, and the processing industry.

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Data Availability The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Declarations

Conflict of Interest The authors declare no competing interests.

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