Chapter

Apical Rooted Cuttings Revolutionize Seed Potato Production by Smallholder Farmers in the Tropics

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Abstract

Potato apical rooted cuttings (ARC) originating from juvenile simple rounded leaf mother plants are a significant new way of transplanting and field growing of seed potatoes under smallholder field conditions in the tropical highlands. The aim of this paper is to highlight the development of the technology by researchers and farmers in Vietnam, Philippines, Kenya and Uganda. The development of cultivars with late blight resistance for which no source of tuber seed was available stimulated the creation of using ARC. The demystification of tissue culture by the 1980s greatly aided this development. The key hurdle was to multiply tissue culture plants in beds of growing media and maintain the physiological young stage of the mother plants from which apical cuttings could be repeatedly taken for several months to produce ARC for sale to farmers who demanded the new cultivars (cvs) with all the desirable attributes. The technology was first developed in warmer climates at lower elevations of less than 1,500 meters above mean sea level (mamsl) but gradually it was successfully developed at cooler climates in East Africa. The technology is well established in the highlands of Vietnam and Philippines. The largest family operation is producing over 4 million ARC annually. These high-quality ARC along with improved cvs have markedly improved yields of smallholder farmers, improving food security and increasing their income levels. In Kenya and Uganda there is a rapid adoption of ARC by seed producers, smallholder farmers and youths. The ARC revolution is bringing a great deal of excitement and promise of prosperity to remote poor highland communities.

Keywords: Apical Rooted Cuttings, tissue culture, juvenile mother plants, seed potatoes, smallholder farmers, food security

1. Introduction

Potatoes, the third most important food crop globally, is a major crop for both food security as well as income in many tropical countries. Millions of smallholder resource poor farmers now grow potatoes. Productivity measured as harvested yields remains low in comparison to the yields obtained by European and North American farmers. The USA has an average yield of 49.8 t/ha as compared to less than 11 t/ha for countries in East Africa and 15 t/ha for the Philippines and Vietnam [1]. One of the primary reasons for this disparity is the lack of quality seed potatoes of suitable cvs. The continual reuse of seed stocks for many generations leads to severe virus infection. Bacterial Wilt infected seed caused by *Ralstonia solanacearum* further hinders potato production in the mid elevation tropical settings [2].

Traditional western seed potato production systems have been copied in many tropical countries with minimal success. Prevalence of soil borne diseases and virus diseases build up over several generations of seed propagation coupled with prolonged seed storage at warm ambient temperatures are major constraints. The amounts of tuber seed produced are a small fraction of the actual seed requirements, the cost is prohibitive and often seeds of desired cultivars are not available at the right time. Seed importation fills a small gap in the seed requirement of wealthier farmers in some countries.

Over the past 40 years, there has been a major push towards developing suitable seed systems in various countries with donor support and expertise from the International Potato Center (CIP) as well as experts from numerous national and international agencies. China has strongly supported a diverse set of measures using tissue culture, large scale greenhouses for mini tuber production both in substrate as well as in aeroponic systems. Government subsidies were a key part of this success both for capital investments as well as subsidized pricing for the buyers of the mini tubers. India has developed a large-scale seed production system which primarily benefits larger landowners who have the financial means to provide all the needed inputs to grow higher yielding crops from certified or higher standard seed potatoes grown in the northern isolated areas of the country.

Unfortunately, majority of smallholder farmers in most tropical countries did not benefit from these seed systems and yet grew potatoes as a food and income security crop. Potato production, although yields were exceptionally low, still fit into their cropping systems and was also considered a valuable cash crop. Two factors started the change in the opportunity for smallholder farmers to get better quality planting materials. During the 1970s there was an international focus stimulated by CIP on evaluating cvs with late blight (*Phytophthora infestans)* resistance in many parts of the tropical world. Cvs with superior resistance to late blight proved to be a large benefit to farmers who could not afford or access fungicides. Farmers expressed high demand in these new cultivars but there was no immediate source of seed potatoes. The second major development was the modernization and simplification of the use of tissue culture. Rapidly, the technical aspects of tissue culture were being learned and adopted by young scientists, technicians, and private businesses in many developing countries. CIP started distributing these new late blight resistant cvs for evaluation in different countries of South East Asia and Eastern Africa.

2. Principles for successful utilization of apical rooted cuttings as transplants for tuber production

The physiology of the transplant is the most important factor in maximizing the growth and productivity in the greenhouse or field for tuber production. During the 1970s and 80s the use of stem cuttings became a rapid way of producing mini tubers in substrate in greenhouses. These stem cuttings generally originated from a sprouted tuber and always had compound leaves indicating physiological maturity thus yielding only a 2–5 tubers per stem cutting. With the popularization of tissue culture, the plants *in vitro* had simple rounded juvenile leaves and such tissue cultured plants, when transplanted to a substrate, produced many tubers, often exceeding 15 per plant. This leads to the thinking that if the juvenile plantlets with simple rounded leaves could be maintained in a substrate and from which apical cuttings could be taken periodically over an extended period, a large number of ARC could be obtained. Once transplanted to the field, many tubers could be obtained as first field generation seed tubers (G_1). It is critical to maintain the mother plants in a juvenile simple rounded leaf state and then the apical cuttings would develop into excellent ARC for transplanting to the field [3, 4]. **Figure 1a** and **b** illustrates the desired physiology of the mother plants and the ARC. **Figure 1c** shows the initial phase of compound leaf formation. Depending on the genetic background of the cv, these would be discarded as these would not develop into a high tuber producing plant.

Environmental factors are also important to consider in a successful maintenance of rapidly growing juvenile mother plants in substrate filled beds. The tropical environments are generally in the 11 to 13 hour photoperiod range, which is conducive for tuberization. Extending day length to 16 hours improved apical

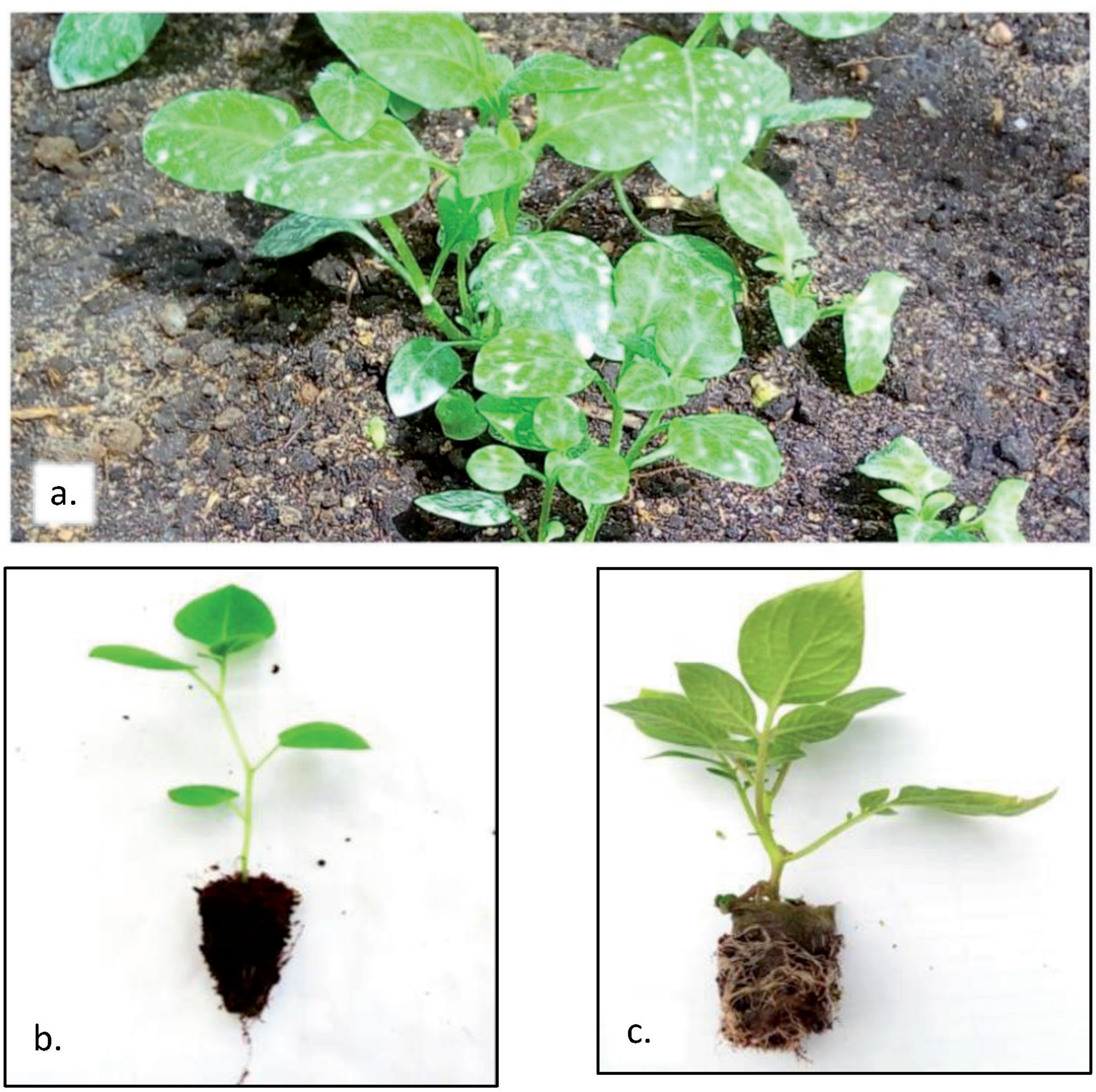

Figure 1.
Mother plants and rooted cuttings: a. Tissue culture origin mother plants maintaining the juvenile simple round leaf stage; b. Apical rooted cutting with simple rounded leaves; c. Apical rooted cutting with undesirable trait of already developing compound pointed leaves.

cutting production [5]. Photoperiod is easily prolonged by turning some lights on during the evenings over the mother plant nurseries. A light break of 1–2 hours is sufficient to simulate the effect of extended day length. Warmer air temperatures encourage rapid growth of the plantlets and their regrowth after harvesting apical cuttings. Minimum air temperatures above 16°C are ideal such as in Dalat [3] at 800 to 1,500 mamsl and in the Philippines at 800 mamsl [5].

At higher elevations, a proper greenhouse may be needed. At lower elevations, productivity is substantially reduced due to overall heat stress with minimum and maximum temperatures above 23°C and 31°C, respectively [6]. Reducing the light intensity through shading also helps to delay physiological aging and naturally delays tuberization.

Most cultivars can be maintained in a young vegetative stage up to 6–9 months with appropriate nursery management with extended day length, warm temperature, and appropriate spacing and fertilization [7]. Gibberellic Acid (GA_3) application was helpful for some cultivars but was later not being practiced. The use of hormones is not necessary when rooting ARC.

Interplay of factors would affect the survival, growth and yield of ARC in the field. Availability of water at transplanting and during the growth cycle is crucial for better survival and yield of transplants. In earlier studies, the most important factors that would influence growth and yield were determined. Cuttings perform better when planted in raised beds compared to planting in flat beds or furrows. Hilling up improved tuber yield (size, number, and weight) and reduced greening of tubers. Pruning of the apical shoot after transplanting did not stimulate more branching nor improve yields. Plant populations greater than 40,000 transplants/hectare did improve total yields but reduced average tuber size. The highest yields were at 100,000 plants/hectare. The cost benefit ratio and the goal of the field production will determine the ideal spacing in each season for most varieties. In terms of fertilization, nitrogen supply was the most important, as deficiency or excessive nitrogen supply reduced yield [4].

Genetic background of the cultivars being utilized is a major consideration. Generally, the cultivars from *Solanum andigena and Solanum phureja* backgrounds are most prolific and remain longer physiologically young. This is partially because tuber induction in these species is not so strong at 11–13 hours of photoperiod. Most *Solanum tuberosum* cultivars, are adapted to the longer days of Europe or other temperate climates and are strongly induced to tuberize under the short-day tropical conditions. Cv Igorota, a cultivar bred with Peruvian germplasm produced 3 times as many apical cuttings as compared to the European cv Granola in a trial in the Philippines [2].

Knowing the cultivars as well as the environment and managing them appropriately are essential for successfully launching a program of mass production of ARC and their transplanting in the field for further multiplication.

3. Vietnamese farmers demystify sophisticated tissue culture technology for the successful utilization of apical rooted cuttings as transplants for tuber production

3.1 Background

Potato production was severely negatively impacted by the post war period in Southern Vietnam with a lack of clean healthy seed potatoes for viable potato production. That, coupled with a lack of good cultivars, placed the farmers and researchers in a difficult situation. The Center for Experimental Biology requested

CIP for new cultivars with resistance to Late Blight. A total of 16 cvs were received as virus free tissue culture plants. After some quick field evaluations there were 3 cultivars that the farmers demanded. With no source of seed tubers available, farmers took it upon themselves to take the tissue cultured plants and multiply them *in vitro* and then to establish the plantlets in a substrate as mother plants from which cuttings could be taken and after rooting, be transplanted to the field [3, 8]. With the support of researchers, farmers quickly learned how to maintain *in vitro* plants with the use of coconut water and some supplemental nutrients in a corner of their bedrooms with plastic walls and a Bunsen burner for sterilization. Then through trial and error, a suitable substrate media was developed using subsoil, sand and fine coconut husk material, composted manure and other materials to grow the mother plants.

Initially, 10 farming families established small outdoor mother plant nurseries on less than 100 m^2 of land next to their homes. Nine of those farmers maintained tissue culture plants in their homes [3]. These multipliers were soon selling over 2.5 million ARC in total annually to smallholder farms in Dalat area [8]. With the rapid adoption of the new cultivars, the demand for ARC was reduced and soon only 3 farmers remained with tissue culture plants and mass production of ARC.

3.2 Recent developments in the utilization of ARC by farmers in Dalat and Lamdong Province

Production of G_1 tuber seed directly in the field from ARC is a routine practice in Lam Dong province (1,000–1,500 mamsl). In 2020, there were 4 major ARC propagators who supplied around 5 million ARC to potato growers in the area. The largest multiplier sells 3 to 4 million ARC a year depending on the growers' demand. Some half a million marble size mini tubers were also harvested from the mother plant beds and sold as quality planting materials to the growers. With good agronomic management and plant density of 50–55 thousand per hectare, the average tuber yield of 20–25 tons per hectare (t/ha) has been obtained from the ARC with over half of that being ware potatoes. There were cases that yields of over 40 tons t/ha were obtained and up to 70% were sold as ware potatoes.

Production of the ARC normally starts in May with tissue cultured disease-free plantlets in Dalat. Those are raised in stock plant beds on good substrate, under net house conditions with about 50% shade. The first two or three cuttings harvested from a stock plantlet are used for establishment of mother plant beds (**Figure 2**).

Further apical cuttings are then harvested for production of ARC for the tuber seed production in Dalat and lower elevation areas of Don Dzuong and Duc Trong (1,000 mamsl). The whole process goes through the months of May to October with rigorous application of hygiene measures and crop protection. The transplanting of ARC into the field takes place mostly in November and December with sprinkler irrigation as rainfall is minimal. The ARC are arranged in wooden trays holding 1,000 each (**Figure 3**), and when ready for planting, are delivered to the growers' farms by the multiplier on a truck or taken directly by the grower himself on a motorbike.

Not as in the past, when an apical cutting was rooted in a small hand-made banana leaf pot of the size approximately 2 x 3 cm for planting into the field, ARC are now rooted in a substrate cube of the size 3 x 3 cm (**Figure 4**). The cubes are mechanically produced in mass by a uniquely designed motorized machine. The substrate is basically the same, i.e. a mixture of fine and clean clay loam subsoil, coconut fiber dust and some composted manure. Much of the substrate production operation has also been mechanized to minimize the costs on screening, mixing the component materials and making the rooting cubes.

Figure 2.
Taking apical cuttings from mother plants.

Figure 3.
Rooting of cuttings in wooden trays.

Figure 4.
Rooting of apical cuttings in substrate cubes 3 x 3 cm in size.

Tissue culture is currently carried out in a research institution and three private farmers' laboratories. Expensive test tubes and/or Erlenmeyer flasks have been replaced by plastic bags and boxes or reused serum bottles in raising the *in vitro* plantlets. This helps reduce the cost on culture vessels and labor for washing.

For the last 25 years, only two potato cvs are used for production for fresh market held by farmers, locally namely 07 (internationally known as Utatlan) and PO3 (released as Igorota in the Philippines). Seed stocks are customarily renewed by planting ARC after several generations in field production. Cv PO3 is resistant to several major viruses, thus seed tubers could be retained from ware fields up to 5–6 generations provided no fungal and/or bacterial infections occur, while cv 07 could hold only for 2–3 generations due to its high susceptibility to viruses.

Though many operational techniques have been improvised, the basic steps in the technological line remain the same through the years since the early 1980s: disease free *in vitro* plantlets – stock mother plants trays/beds – mother plants beds – apical cuttings rooted in pots – G_1 seed fields. The improvements take account for the better laboratory equipment, greenhouse facilities, irrigation system, mechanization in the preparation of rooting substrate and pots/cubes and delivery system.

These all, coupled with the great availability of quality pesticides and fertilizers, help assure stability and success of the novel seed potato system in Dalat.

From an economical point of view, the ARC propagation is a profitable business. With the current price of USD 1.75 per 100 ARC, the total revenue of all the multipliers would be USD 87,500 for the 5 million ARC a year. Their net profit is estimated to be about 30% of the amount. A little income would be added from the mini tubers harvested from the mother plant beds. Though the unit price has increased by 2.5 since the early 1990s the proportion of net profit seems unchanged mainly due to the situation that transplanting of the ARC in the field (sale of ARC), take place primarily only during two months (November and December). Whereas the mother plants could be maintained for apical cuttings harvesting for up to 4–5 months [9].

Partly, inflation of inputs, especially the labor cost, adds some strain to improvement of net profit. However, the scenario shows that most of the benefit from the ARC technology has been going to the small holder farmers who make much higher profitability from their potato production owing to the higher quality of planting materials. The fact that the average potato yield in Dalat has been lifted from less than 10 t/ha during the late 1970s to around 15 during the 1990s and 25 at the present is largely attributable to the use of disease-free ARC for seed propagation.

4. Apical rooted cuttings permitted rapid adoption and maintenance of new cultivars for smallholder farms in Philippines

4.1 Background

The Regional Germplasm and Training Center of CIP in the Philippines was established in 1982 to multiply new sets of cvs for distribution and evaluation by institutions in Southeast Asia and the Pacific. ARC were successfully used for quick multiplication of tissue culture plants and the subsequent evaluation of diverse cvs in five different environments in the country [4].

In 1985–1986, ARC field trials were initiated with highland farmers. In some field trials yields were up to 38 t/ha. Based on these preliminary results some farmers were willing to buy ARC at nominal price [10]. In 1990, 3 out of 8 new clones with superior late blight resistance were selected by farmers. LBR1–5 was the most prolific in terms of cutting production while I-1039 and LBR-9 were highest yielders. Four of the clones from cuttings out yielded Granola from tubers (control check) [11]. LBR1–5, later coded as PO3 and officially released as cv Igorota in 2004, was selected for its early maturity, good tuber skin and shape, and high yields with large sized tubers. Cv Igorota was initially multiplied and sold for seed by Mr. Peter Raymundo, a farmer from Buguias, Benquet [2]. The use of ARC made possible the rapid multiplication of pathogen tested materials and introduction of new cvs for on farm evaluations.

4.2 Adoption of ARC and new cvs for commercial potato production

The commercialization of ARC for seed potato production was a concerted effort of government, private sector and farmers' organizations. The Department of Agriculture provided funds for research and infrastructure development; Land Bank provided loans; while Northern Philippine Root Crops Research and Training Center (NPRCRTC) of Benquet State University conducted research, on-farm trials and dissemination of ARC and new cvs. Farmer organizations were multipliers. They bought ARC or *invitro* plants as source of mother plants. The multipliers produced G_0-G_3 seed tubers for other farmers. NPRCRTC and a farmer cooperator were accredited by the Bureau of Plant Industry to produce certified ARC and mini tubers for farmers in Benquet and beyond.

Mr. Nelio Compelio is an outstanding multiplier. He started using ARC in 1992 and *invitro* plants as source of mother plants in 2010. He replaces his seed stocks in 2 years or whenever decrease in yields is observed. He started selling Igorota seed potatoes to farmers in other municipalities in 1995. Now, farmers have the option to buy from him either ARC or seed tubers. He was able to build a big house in Atok and another in Baguio out of his production venture. They call these "Houses that Igorota Built".

Several farmer organizations followed the aforementioned example and supported their members through multiplication of ARC of their preferred cvs. On average, tubers harvested from an ARC field-grown crop can be multiplied 4 times as seed before selling them to other farmers for table or processing potato production. All cooperators attest to the fact that seed production using ARC is efficient and profitable [12].

4.3 Impacts of ARC on dispersal of new/recommended cvs

The use of ARC and the informal seed systems by farmers had greatly contributed to the selection and dispersal of new and improved potato cvs. The dispersal of clean planting materials from NPRCRTC accelerated this process. As example, cvs Montañosa, Dalisay and Igorota were propagated in nurseries and in farmer's fields prior to its release as official Seed Board Varieties. NPRCRTC had sold 353,000 ARC of cv Igorota from 1987 to 1994. To date, 7.8 million pathogen tested ARC and minitubers were sold. The number of farmers served over the years also increased (**Table 1**).

Distribution of different cvs continues to the present. The most popular is Igorota with 3,440,000 ARC and 371,000 G_0 mini tubers sold to farmers. The demand for other varieties varied depending on farmers' preferences and market demand (**Table 2**).

Year(s)	No. of Individual Clients	Planting Material ('000's) Distributed to Farmers			
		ARC	G_0 tubers	Total	No. per Farmer
1987–1994		353		353	
1995–1999	305	596	136	732	2.4
2000–2004	226	828	94	922	4.1
2005–2009	752	1,276	121	1,397	1.9
2010–2014	757	1,224	150	1,374	1.8
2015–2019	1,085	1,887	479	2,366	2.2
2020	156	139	152	291	1.9
April 2021	143	138	227	365	2.6
Total	3,424	6,441	1359	7,800	
Mean					2.3

Table 1.
Planting materials distributed by NPRCRTC from 1987 to April 2021.

Cultivar	ARC and Mini tubers Sold ('000's)				
	2006–2010	2013–2017	2018–2020	January to April-21	Total
Granola					
a. ARC	94	184	140	5	423
b. G_0 Tubers		62	185	194	441
Igorota					
a. ARC	1,280	1,544	487	129	3,440
b. G_0 Tubers		189	167	15	371
Other cvs					
a. ARC	30	26	76	4	136
b. G_0 Tubers		14	45	17	76
Total	1,404	2,019	1,100	364	4,887
a. ARC	1,404	1,754	703	138	3,999
b. G_0 Tubers		265	397	226	888

Table 2.
ARC and G_0 mini tubers sold by NPRCRTC from January 2006 to April 2021.

The NPRCRTC estimated production cost for ARC is 0.0210 USD/piece while the selling price is 0.031 USD/piece. The production cost and selling price per piece of *invitro* plant is 0.23 USD and 0.314 USD, respectively. Whereas, the G_0 is produced at 0.0858 USD and sold at 0.104 USD per piece.

5. Kenyan private and public sectors develop and rapidly promote ARC technology for farmers

5.1 Background

In Kenya, potato ranks the second most important crop after maize and is cultivated in the high-altitude areas between 1,500 and 3,000 mamsl [13]. Production is mainly rain-fed and is done in the long and short rains that occur in the period of March–July and October–January, respectively. The public institutions mandated to produce breeder seed or pre-basic seed potatoes can only meet about 1 to 2% of the certified seed demand in the country [14, 15]. These institutions mainly adopt the conventional clonal multiplication in which a set of disease-free tubers is repeatedly multiplied to bulk the seed. However, this method has low multiplication ratios of 3–6 and cannot meet the national seed demand. Certified seed is therefore highly priced in Kenya (at a cost of USD 30 to 40 per 50 kg bag) and is estimated to account for 20–70% of the total production costs. This compels farmers to use seed tubers obtained from informal sources. Such seeds are often infected with bacterial wilt and potato cyst nematode, thus resulting in low yields, poor quality produce, and spread of pests and diseases. The obtained potato yields are generally low with an average of 10 t/ha [16] against the potential of 30–40 t/ha [1, 13].

It is against this backdrop that CIP in partnership with the private sector Stokman Rozen Kenya (SRK), Kenya Agriculture and Livestock Organization (KALRO), Kenya Plant Health Inspectorate Service (KEPHIS- a body regulating seed certification in the country), and private businesses, sought to explore ARC as a complimentary rapid seed multiplication technique. The new improved CIP cvs: Unica, Wanjiku, Nyota, Chulu, Lenana and Kongo have been trialed against the conventional cv Shangi. Yields obtained from ARC have been robust and average 8–18 tubers per plant depending on the cv and management (**Table 3**). Subsequently, ARC has been endorsed by KEPHIS into the seed certification protocol to bulk up seed potato for multiplication and distribution to potato growers.

5.2 Taking ARC technology to farmers' doorstep

At least 10 satellite nurseries investing in apical cutting production have been set up in Meru, Nakuru and Nyandarua counties. Four of these nurseries were initiated by Farm Inputs Promotions Africa and CIP, and each has a capacity to produce 100–200,000 ARC annually. World Food Program in partnership with CIP has supported additional 2 satellite nurseries. Two other commercial private nurseries (Grace Rock Ltd. and SRK) have incurred great investments in ARC production with capacity to each produce up to 1 million ARC annually.

5.3 Juvenility of the mother plant- Kenya's case

As noted across the nurseries, mother plant productivity is highly dependent on the prevailing environmental conditions and routine management. Maximum productivity, vigor and mother plant juvenility has been associated with temperatures of about 18-25°C, relative humidity of 60–85%; regular fertigation with adequate nitrogen applied at 2–3 day intervals and use of clean media that exhibits low salt concentration (EC <0.5 dS/m), pH 6.0–6.5, and can retain good moisture and nutrients). Cocopeat is the most commonly used media in Kenya. However, if not properly washed, cases of stunted growth, yellowing and even death of the ARC have been reported. As observed by most multipliers, frequent cutting of the mother plant extends juvenility up to 9 months. Cuts should be obtained as soon as apical shoots have grown 5–7 cm high, or if the shoot has 4–7 complete leaves with 2–3 internodes. This is a key management protocol to attain prolific and juvenile mother plants. With regular proper training, nursery multipliers can vividly differentiate a physiologically young mother plant which they measure by simple round leaves, dark green vigorous shoot, delayed tuber formation/shoot senescence, and stems which are soft and easy to root in the absence of rooting hormones (**Figure 1a** and **b**). The commercial apical cutting derived from a juvenile mother plant has the bottommost leaves round and simple as opposed to the compound leaf characterizing the cutting derived from a mature mother/stem cutting (**Figure 1c**). A mature mother plant literally gives stem cuttings with low multiplication ratio of 3–7 tubers/cutting; thus, the multipliers are made aware that only juvenile plants are propagated to result in high rates of ARC production. To rescue a mature mother, the multipliers cut back the plant as soon as compound leaves are evident. Once the mother plant is too old to be rejuvenated, it is transferred for mini tuber production.

County	#of farmers sampled	#of tubers >20 mm					
		Shangi	Unica	Wanjiku	Nyota	Konjo	Chulu
Kiambu	96	11.5	8.8	18.2	13.9	10.9	10.8
Nakuru	24	12.8	9.3	18.2	14.5	10.3	11.6
Uasin Gishu	16	14.4	9.7	17.6	13.2	9.5	10.5

Table 3.
Average tubers per plant obtained from six potato cvs sampled from a total of 136 farmers. Sampling of at least 140 plants was randomly done from farmers who received ARC in Kiambu, Nakuru and Uasin Gishu in the long rains 2020.

5.4 Submothering for rapid ARC multiplication

With the technical guidance from CIP, the nurseries have adopted the practice of submothering to enhance rapid multiplication. The practice derives 1 to 2 submother plants from the first 1 to 2 cuts obtained from an *in vitro* plantlet. The submothers are only derived from a very juvenile tissue culture derived mother plants (<1 month) that exhibits dark-green vigorous shoot with all round and simple leaves. Submothering allows rapid multiplication rates of high potential *invitro* derived mother plants and can help attain multiplication rates up to 70 ARC per tissue culture plant in a 4 month period just like the case of Grace Rock Farm Ltd. (**Table 4**).

5.5 Making ARC a demand driven technology

Building market demand becomes key to accelerate the uptake of ARC. Thus, over the last few years, CIP in partnership with KALRO and county governments have built capacity of more than 200 extension agents to train farmers on ARC production. Women and youth groups have been supported to develop into small businesses. Additionally, CIP has built capacity of public agriculture training centers (ATCs) and supported the formation and registration of potato cooperative societies and private seed multipliers. Some of the cooperatives have been licensed as seed merchants and have acquired over 100 acres of land for seed multiplication. A few seed potato businesses now operate as out growers using ARC as starter seed material.

Increased sales of ARC have been observed across businesses licensed to produce and sell ARC. For example, farmers privately purchased 417,311 ARC in 2020 from 8 nurseries valued USD 42,000, while CIP purchased 168,000 for training and promotional purposes. The purchase made by the farmers were directly related to the trainings and field demos conducted in the preceding period, and generally indicated high preferences and acceptance of the new improved CIP potato cvs (Unica, Nyota, Wanjiku and Chulu). Benard Mwaura, a crop officer in Kiambu County, reported that “farmers are able to appreciate the rapid seed multiplication rates with the ARC technology and are so impressed that some of these cvs have good resistance to late blight and can tolerate water stress”. Particularly, Wanjiku cv has gained popularity in Meru, Nakuru and Kiambu counties due to its good table qualities, and high multiplication rates ranging up to 50 ARC/tissue culture plantlet (**Table 5**). Cv Chulu was noted by farmers to be resistant to late blight while cv Unica has been preferred for its fast maturity and ability to tolerate heat and water stress.

Cultivar	#in-vitro plantlets used	#sub mothers produced	Total mother plants (*invitro* + sub mothers)	Total cuttings produced	Multiplication Ratio
Shangi	250	388	638	45,342	71
Unica	100	147	247	17,697	72
Wanjiku	150	132	282	16,617	59
Chulu	100	98	198	9,900	50
Nyota	50	33	83	3,513	42
Konjo	100	90	190	5,242	28
				98,311	

Table 4.
Total quantity of ARCs produced from combined mothers and sub mothers, and average multiplication ratio by six potato cvs obtained by Grace Rock Farm Ltd. in the period of March to December 2020.

Decentralized ARC producers	Location	Elevation (masl)	Cultivar			
			Shangi		Wanjiku	
			# *invitro* plantlets used	**Ratio**	**# *invitro* plantlets used**	**Ratio**
Cecinta Nduru	Meru	2,360	200	50	720	13
Mary Nkatha	Meru	2,360	250	37	500	29
Robert Kimathi	Meru	2,023	325	19	300	24
Paul Munene	Meru	1,710	413	7	697	28
Faith Kajuju	Meru	2,222	270	13	—	
Erick Bittok	Nandi	2,006	2,196	3	1,071	4
Potato Empire	Nakuru	2,790	379	46	200	15

Table 5.
Invitro *plants used and average multiplication ratio for two cvs by privately owned satellite nurseries in the period of September 2020 – April 2021.*

6. Ugandan private and public sectors develop and rapidly promote ARC technology for farmers

6.1 Background

Potato is a key food and cash crop in Uganda, grown primarily by smallholder farmers in the eastern and southwestern highlands of the country. There are two major potato growing seasons (March–July; September–January), however, some off-season production also occurs in swamps, valley bottoms and irrigated areas.

National potato production has grown steadily over time, responding to an increasing demand and consumption [17]. This increase in production has been obtained by expanding the land cultivated rather than by increasing productivity [1]. Currently, Ugandan potato farmers harvest an average of 3–12 t/ha [18, 19]. The primary reason for this low yield is the use of low-quality seeds, that farmers recycle from previous harvests or purchase from other farmers or in the local markets [20]. Such seeds are often infected with seed-borne pathogens.

To improve farmers' access to high-quality seed of desired cvs, and to unlock the yield potential of potato in Uganda, CIP and other development partners have supported decentralized seed multiplication for more than a decade. Decentralized seed multipliers (DSMs) are based in potato growing communities and use early generation seed (EGS) – mostly basic seed – as starter material for onward field multiplication and bulking. DSMs have the advantage of making seed available in proximity to ware potato farmers at affordable prices. Quality assurance is the main risk to seed production under a DSM approach, but can be addressed with effective system management.

DSMs in Uganda, however, are frequently confronted with a lack of quality basic seed because public and private seed producers do not generate enough seeds to assure these demands. The current seed potato production system in Uganda is relying on the production of mini tubers from *invitro* plantlets in the screenhouse, followed by two seasons of field multiplication to produce basic seed. Public agricultural research institutes are currently leading the country's seed potato production. Private sector investment in commercial seed potato production is small and consists mainly of a few farmers in potato producing areas managing small screenhouses producing EGS and bulking seed in the field [21].

6.2 Recent developments in the utilization of ARC by farmers in Eastern and Southwestern Uganda

In 2019, CIP partnered with public agricultural research institutes, farmer managing screenhouses and a private commercial company to promote production and field multiplication of ARC. This initiative was to address the challenge of accessing tuber seed for farmers. The partners were trained and supported to produce ARC. The locations of their operations varied from 1,200 to over 2,200 mamsl (**Table 6**).

Nursery	Type of nursery	Location	Elevation (mamsl)	# *invitro* plantlets used	Ratio	Number of cvs	Sale price (USD)	ARC Sold
Agromax Ltd.	Private	Kampala	1200	8,824	12.5	8	0.2–0.25	81,510
Farmer Greenhouse managers	Private	South western and Eastern Uganda	1,665-2,433	11,335	12.9	8	0.11–0.25	51,902
KaZARDI	Public	Kabale district (South western Uganda)	2,223	5,119	18.9	2	0.28	2,550
BugiZARDI	Public	Bulambuli district (Eastern Uganda)	1,760	4,250	5.9	4	—	0

Table 6.
Different nurseries in Uganda producing ARC and their results during 2019 and 2020.

Figure 5.
Seed multiplier in a seed plot with potato plants from ARC.

DSMs were trained in field multiplication techniques to produce tuber seed of different cvs from ARC as illustrated by a smallholder field crop growing from ARC in **Figure 5**.

The NGO Self Help Africa was a key partner in implementing and monitoring field activities. The ARC multiplication rates varied among nurseries and cvs planted. The highest multiplication rate of producing ARC/tissue culture plant was at the KaZARDI in Kachwekano. The most popular cvs demanded by the smallholder farmers were: Victoria, Kachpot, Rwangume and Kinigi.

Despite the immense advantages of ARC for seed production, five major challenges are being addressed: to sell ARC at an affordable price depends largely on improving the multiplication rate of mother plants from tissue culture; improved cost-effective, easy-to-manipulate, locally acceptable, and environmentally-friendly packing materials that can maintain the quality of the ARCs during transport; improve transplants survival and tuber yields; a better coordination among potato value chain stakeholders to develop and stabilize the market demand for ARC and avoid oversupply; and quality assurance mechanisms need to be developed and implemented to use ARC in certified seed potato production that is aligned with the seeds and plants regulations of Uganda.

7. Discussion

The development and utilization of ARC in the 4 countries have some significant commonalities and differences. The initial primary driver of adopting the use of ARC is the highly desirable characteristics of the cvs sought by the smallholder farmers in each country. Improving the access of seeds of cultivars resistant to late blight was the most significant initial reason for the trial and adoption of ARC. The cvs mentioned in each country were either derived from CIP shared germplasm or coming from the Mexican late blight resistance selection program prior to 1975. Cvs Igorota (PO3) and Utatlan are the prime examples for the Philippines and Vietnam. The cvs promoted in Kenya and Uganda are all from CIP germplasm with moderate late blight resistance. These cvs proved to be vastly superior for late blight resistance compared to European cvs for which seed could be imported. This factor was the primary driver for the rapid acceptance and utilization of tissue culture and the mass production of ARC.

The successful development of juvenile rounded simple leaf ARC after many months of maintaining mother plants in the juvenile stage allowed the transplants to develop in the field to large vigorous plant with only one primary stem producing on average 11 and 18 tubers/plant. This has been the case in all 4 countries. This productivity is equal to that of standard seed tuber planted crops with 3–4 stems/plant. The climatic conditions for maintaining juvenile mother plants were initially at elevations of less than 1,500 mamsl in Vietnam and the Philippines. These warmer conditions favored rapid growth and frequent harvesting of apical cuttings. Interestingly in both Kenya and Uganda the productivity of juvenile mother plants can be maintained at cooler higher elevations above 2,000 mamsl. Better greenhouses and seasonal considerations as well as adding temperature control measures improved productivity.

The demand for ARC has stabilized in the highlands of both southern Vietnam and the northern Philippines. The high level of virus resistance of cv Igorota (PO3) permits the G_1 seed to be regrown by farmers 5–7 times before replacing with new ARC. In the case of Dalat Vietnam, when bacterial wilt appears in a field crop, it will not be retained as seed for replanting. For the approximate 1,500 hectares of potatoes grown in the greater Dalat area a total of about 5 million ARC are sold annually.

In the Philippines highlands with an area of about 7,500 hectares in potatoes annually, approximately 350,000 ARC plus 100,000 mini tubers are demanded annually from NPRCRTC. Many small holder farmers multiply the ARC further.

In Kenya, there was a rapid growth phase in the acceptance of ARC as the technology allows to have virus free planting material of cvs with late blight resistance and other good attributes. Licensed seed merchants can now use ARC as starter materials to produce certified seeds. Uganda is at an earlier stage in the introduction and adoption of ARC.

There is a large difference in the selling price of 100 ARC among 4 countries. In Vietnam, the price is USD 1.75; Philippines 3.00; Kenya 10.00 and Uganda is 11.00–26.00. The producers of ARC in Vietnam calculate a return to labor and investment of 30% while in the Philippines it is 24%. The largest producer in Vietnam prepares 100,000 tissue culture plants in May. These are placed in the substrate beds and multiplied to 720,000 mother plants by September. Then for 2–3 months apical cuttings are harvested and rooted every 5 days. Over 4 million ARC will be sold to smallholder farmers by December when the transplanting season ends. The large-scale efficiency in the production process allows this producer and the others in Dalat to sell 100 ARC at USD 1.75, with a significant profit. The selling prices in the Philippines has stabilized at USD 3.00/100 ARC. ARC sold per single tissue culture plant is greater than 40. In Kenya, the multiplication rate is similar with some cvs such as Shangi and Unica reaching 70 ARC/tissue culture plant. In Uganda, these numbers are still generally less than 20. Production costs and selling prices will be lowered through efficiencies in Kenya and Uganda as the technology matures and competitors join in the business.

Impact of the ARC technology coupled with new desired cvs had made a marked difference in the level of food security and prosperity for the smallholder potato farmers in all countries. In Southern Vietnam, it is estimated that the average yield of potatoes has improved from 10 to now over 25 t/ha due to clean seed of late blight resistant cultivars. In the Philippines, a similar improvement has been observed over the past 20 years with yields of 40 t/ha frequently recorded. The impact is seen in the purchases of refrigerators, motorcycles, and other household amenities. One multiplier of ARC in Dalat even purchased a baby grand piano! In the Philippines, there are stories about houses built on the production and sale of ARC and G_0 mini tubers by some farmers. In general, all smallholder farmers who have opted to grow ARC and G_0 mini tubers have improved food production and generated more income.

The ARC technology will continue to face strong competition from European tuber seed for the larger seasonal lowland production systems after rice and in the semi-arid regions of North Africa. Upland mountain area of India and other parts of Africa will be conducive for ARC adoption, especially where the planting season can be prolonged for 2 months or more. Aeroponics is an established system in high temperate locations of China, India as well as in other localities in South America and some in Africa to produce mini tubers. The level of sophistication with the need for reliable electricity, however, limits its adoption and favors the use of ARC in most tropical environments where potatoes are grown.

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