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Seed Yam Production Using High-Quality Minitubers Derived from Plants Established with Vine Cuttings

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Abstract: Yam (*Dioscorea* spp.) is a valuable food security crop in West Africa, where 92% of the world production occurs. The availability of quality seed tubers for increased productivity is a major challenge. In this study, minitubers weighing 1, 3, and 5 g produced from virus-free single-node vine cuttings of two improved yam varieties (Asiedu and Kpamyo) growing in an aeroponics system were assessed for suitability in seed production at a population of 100,000 plants ha^{-1}. A 3 × 2 factorial experiment with randomized complete block design and three replications was set up during the cropping seasons of 2017 to 2019 at the International Institute of Tropical Agriculture Research Station in Kubwa, Abuja, Nigeria. Results showed field establishments of 87%–97.8%. Yields differed with minituber size, variety, and cropping season; the highest was 31.2 t ha^{-1} in 2019 and the lowest, 10 t ha^{-1} in 2018 from 5 and 1 g Kpamyo minitubers, respectively. The estimated number of tubers produced per hectare by 1, 3, and 5 g minitubers was 101,296, 112,592, and 130,555, with mean weights per stand of 159.2, 187.3, and 249.4 g, respectively. We recommend using less than 6 g minitubers for seed yam production due to their high multiplication rates.

Keywords: *Dioscorea rotundata*; minituber; seed yam; production

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1. Introduction

Yam is a tuber crop of the genus Dioscorea and the family Dioscoreaceae, of which the most important species used as food are *D. rotundata* Poir (white yam) and *D. alata* L. (water yam). It is an important staple crop that is mainly grown in tropical regions of West Africa, the first and Asia the latter. Yam is produced primarily in the savannah region of West Africa, which contributes 92% (66.8 million tons) of the world yam production of 72.6 million tons [1]. Nigeria, Ghana, and Côte d'Ivoire together have 86% of world production.

Yam plays a vital role in enhancing food security and alleviating hunger in many parts of West Africa [2]. It contributes substantially to the human diet as a significant source of energy. The yam value chain provides income-earning opportunities to its producers, processors, and sellers. It is also a source of pharmaceutical compounds, such as saponins and sapogenins [3], and its peels can be used as feed for livestock [4]. Yam is the only crop that is usually celebrated during and after harvest with traditional festivals [5–7] in the West Africa region.

Yam productivity has been on the decline despite the increasing demand for local consumption and export. This decline in productivity can be attributed to several problems: high labor demand, high cost of cultural operations, pests and diseases, declining soil fertility, unpredictable weather conditions, and the lack of quality planting material [8,9]. In Nigeria, the scarcity of quality planting material is critical, affecting both commercial and subsistence production. The high cost of planting materials, which can be up to 62% of the total production outlay [10], encourages the competition between edible and seed tubers [11]. Hence, the need to seek alternative propagation methods to resolve issues related to the availability of planting materials, especially on a commercial scale.

In a pre-project study of the "Yam Improvement for Income and Food Security in West Africa (YIIFSWA)" project of the International Institute of Tropical Agriculture (IITA), it was noted that in West Africa, out of the attainable yam yield of 22 t ha^{-1}, there was a gap of 11.2 t ha^{-1} due to several factors. The most important of these are poor quality seed, low soil fertility and use efficiency, drought, weeds, and diseases, all contributing to 9.1 t ha^{-1} of the yield gap [12]. Virus infection specifically contributed to almost 10% of the yield gap. With this background, the YIIFSWA project had an objective to establish viable and sustainable yam seed systems in the two highest yam producing countries, Nigeria and Ghana. The project started by cleaning available planting materials of viruses before the investigations into various techniques of multiplying the crop commenced.

Conventionally, yam is propagated using tubers, which also serve as food. Large chunks of tubers weighing up to 500 g are planted to harvest both ware and seed yam. In this method, the seed is sorted from the ware yam, thus reserving about 150–1000 g tubers to plant the next crop. In traditional systems, the tubers multiply slowly with a multiplication ratio of 1:3; hence there is a perpetual under-supply of seed tubers at planting time, especially for first-time yam producers and farmers seeking to expand production. The yam minisett technique (YMT) of propagation was developed [13,14] to improve multiplication and seed availability. It involves cutting yam tubers of less than 1000 g into small pieces of 25–30 g to produce seed tubers, which are then used for ware yam production. This technique was the first attempt to separate the seed from ware yam production, increasing the sett multiplication ratio to 1:30. Another benefit of this technique was reducing the number of yam tubers used as planting material instead of food.

An attempt was made to produce minitubers using a progeny of microtubers from in vitro derived plantlets [15]. Ahloowalia [16] similarly produced small whole tubers by growing micro-propagated potato plants or micro-tubers in vivo in green- or screen houses, or directly in the field. Seed yam production using minitubers was intended to build a bridge between in vitro rapid multiplication and regular field production of seed tubers. Producing seed yam using minitubers was developed in 2003 by the National Root Crops Research Institute (NRCRI), Umudike, Nigeria, as a backup for the YMT [17]. The NRCRI study summarized yam tuber size classifications by different authors as follows: <50 g = microtubers; 50–99 g = mini seed yam (minitubers); 100–249 g = seed yam grade 2; 250–1000 g = seed yam grade 1; and >1000 g = ware yam. The minitubers were reported to produce seed yams of up to 900 g when planted in good soil. It was also claimed that the minituber production technique was to enhance uniformity in seed yam sizes for export and to reduce the scarcity and high cost of seed yams often experienced by farmers [18].

However, research on increasing yam's multiplication rate and preserving more tubers for food has continued. Earlier attempts to use yam vines for propagation showed that it was possible. Still, several challenges limited the degree of success related to the poor establishment and the tiny tuber size produced [19,20]. Recent work at IITA has shown that yam vine cuttings can be used successfully with novel techniques for large-scale seed yam production. The plantlets from temporary immersion bioreactors (TIB) are planted in an aeroponic system (AS) and other hydroponics systems to rapidly propagate the crop [21,22], producing different sizes of tubers, as well as vines used for further multiplication as single-node cuttings. These methods can increase the multiplication ratio to 1:300 and more. In the AS, plant roots grow continuously or discontinuously in an environment saturated with a nutrient solution mist [23]. Freshly cut two-node vine cuttings or pre-rooted single-node vines planted in the AS produced minitubers ranging from 0.2 to 110 g depending on the genotype, plant age at harvest, and composition of the nutrient solution [21]. The system allows for a rapid multiplication rate and enhances seed yam production in the field, reducing the scarcity and high cost of both seed and food tubers [3].

This study's objective was to investigate the yield potential of whole minitubers below 6 g, derived from virus-free vine cutting seedlings obtained from yam plants grown in an AS. Unlike the classification given by NRCRI [17], the below 6 g tubers used in this study are referred to as minitubers because microtubers are considered to signify products of micropropagation in tissue culture.

2. Materials and Methods

The trials were conducted at the Kubwa station of IITA, Abuja, Nigeria, during three cropping seasons from 2017 to 2019. The research station is in Nigeria's "Yam Belt" at 9°09′51.6″ N, 7°20′44.6″ E, and 424 m above sea level. During the experiments, the weather data collected showed that rainfall started in March and stopped in October in 2017 and 2018. In contrast, rain fell from February to November in 2019 (Figure 1), and the total rainfall during the cropping period was 874.2, 1214.7, and 1768.2 mm in 2017, 2018, and 2019, respectively. Monthly rain and temperatures during the cropping seasons are presented in Figure 1. In all the years, the experimental fields were fallowed with *Aeschynomene histrix* Poir., then *Mucuna* spp., before the experiment was planted.

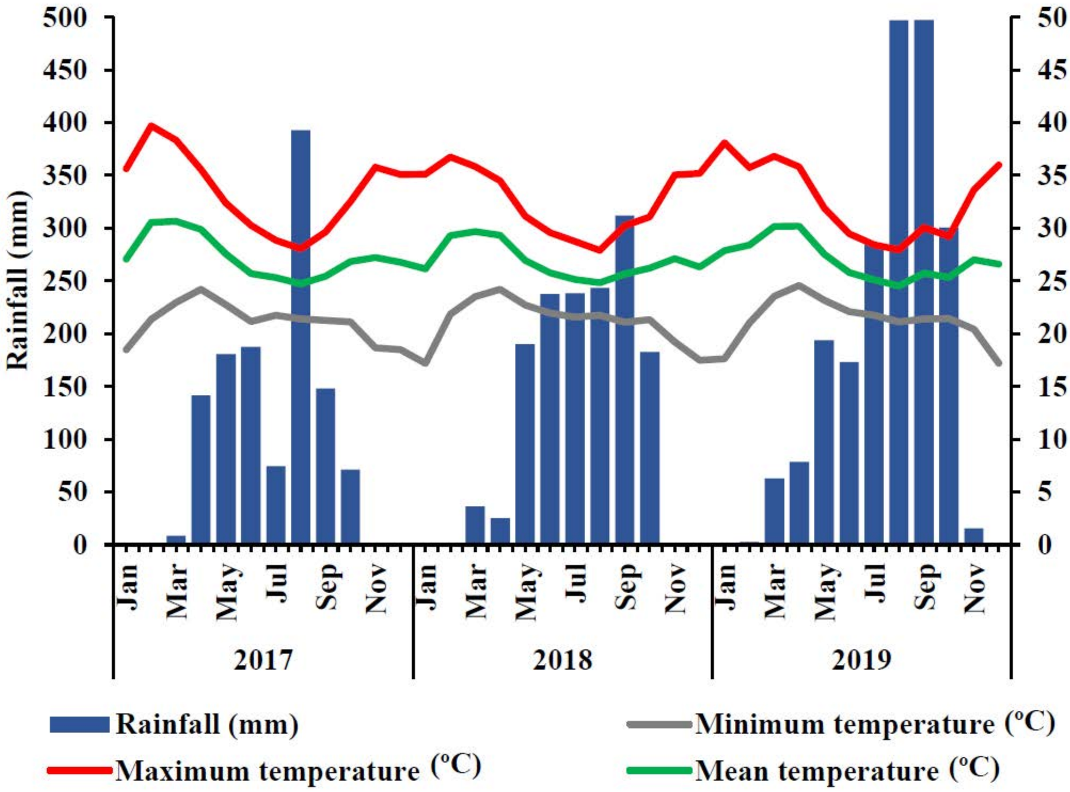

Figure 1. Rainfall and temperature during the cropping seasons from 2017 to 2019 at International Institute of Tropical Agriculture Station, Abuja, Nigeria.

Minitubers of less than 6 g of the yam varieties Kpamyo and Asiedu were used for the experiments. The minitubers were obtained from vine-cutting-derived plants. During the previous year of each trial, yam vines were harvested from virus-free plants in an AS. The vines were cut into single-node cuttings, each with one leaf or two leaves, and planted in black polythene nursery bags or nursery seed trays (Figure 2). Minitubers were harvested three months after planting from the cuttings that rooted but did not produce any shoot. The minitubers were stored in a cool and well-aerated room until dormancy was broken after about three months, evidenced by the appearance of sprouts on the tubers. They were then sorted into three categories by size: 0.1–1.99 g, 2.0–3.99 g, and 4.0–5.99 g, averaged and referred to in this paper as 1, 3, and 5 g, respectively. The minitubers were treated with a chemical mix containing 100 g of Mancozeb and 40 mL of cypermethrin in 10 L of water for 10 min to protect against rot and pest damage. They were air-dried under shade for about 24 h before planting in the field.

Figure 2. Production of minitubers. 1 = Yam plants in an aeroponics system; 2 = Nodal yam cuttings planted in a polystyrene nursery tray (Cuttings without shoots were allowed to produce minitubers, those that formed shoots were transplanted to the field); 3 = Minitubers produced after three months from single leaf cuttings (without shoots); 4 = Sprouted minitubers used in the experiment.

At the beginning of each season, poultry litter was applied at the rate of 10 t ha^{-1} to the experimental field before it was disc-harrowed and made into 3 m long ridges spaced 100 cm apart. Planting was done on top of ridges at 3–4 cm depth in single rows and 10 cm between stands on 7, 5, 8 June in 2017, 2018, and 2019, respectively. A 3 m single ridge represented a treatment/plot and contained 30 minitubers. The seed rates for 1, 3, and 5 g minitubers were 100, 300, and 500 kg ha^{-1}, respectively, with a plant population of 100,000 plants ha^{-1}. The experiment was laid out as 3 $\times$ 2 factorial, fitted into a randomized complete block design (RCBD) with three replications and six treatments.

At one week after planting (WAP), the plots were sprayed with a herbicide mixture of Premextra (290 g L/S-Metolachlor, 370 g/L Atrazine at 5 L ha^{-1}) and Gramoxone (200 g/L Paraquat at 5 L ha^{-1}), after which a hand-held hoe was used to remove weeds, earth-up the plants and reform the ridges. Staking of young plants started 6 WAP and lasted for two weeks as plants attained 4–6 open leaves. The staking was done using the trellis system, where ropes were tied between two strong bamboo poles placed at the beginning and end of each ridge, and strings used to direct the plants to the rope. Fertilizer was applied at the rate of 400 kg NPK (15:15:15) ha^{-1} [24] at 8 WAP using the side placement method.

From six days after planting (DAP), the number of emerged plants was recorded at four-day intervals until 38 DAP. At eight weeks, six plants were randomly selected per treatment, and data collected on stem length (m) and the number of leaves and vines per plant. The leaf area index (LAI) was measured at 12 WAP using the CI-110 digital plant canopy imager, capturing a 1500 fisheye image of the canopy (CID Bio-Science, Bozeman, MT, USA). When vine senescence was complete at the end of the season, tubers were harvested on 15, 19, and 12 December in 2017, 2018, and 2019 corresponding to 27.3 WAP, 28.1 WAP, and 26.7 WAP, respectively. The seed multiplication ratio (SMR) was calculated, as shown below:

$$\mathrm{SMR} = \frac{\text{Weight of harvested tuber (s)}}{\text{Weight of the planted material}}$$

All data were subjected to the analysis of variance (ANOVA) using the statistical analysis system (SAS, 2016). Where mean differences were significant, they were separated with the least significant difference (LSD) at $p \leq 0.05$.

3. Results

3.1. The Effect of Seed Tuber Size and Variety on Crop Establishment

The planted minitubers started emerging from the soil within the first week of planting, although the mean number of days to emergence differed with size. Figure 3 shows the days to emergence, with the 5 g minitubers of Kpamyo and Asiedu being the earliest and were significantly different from the 1 g minitubers of both varieties. Although the increase in the proportion of emerged plants from 1 g and 3 g minitubers was gradual and reached a peak in 38 and 34 days, respectively, that of 5 g was much faster between 18 and 30 days, when Kpamyo peaked at 96.7%. The 1 and 3 g minitubers were similar in their time to emergence (Figure 3). The period to 50% of the plant's emergence from the soil from 5 g minitubers was considerably earlier ($p = \leq 0.05$) than plants from 1 and 3 g minitubers (Table 1). There was generally no difference between the yam varieties regarding the time to 50% emergence and final crop establishment (Table 1, Figure 3).

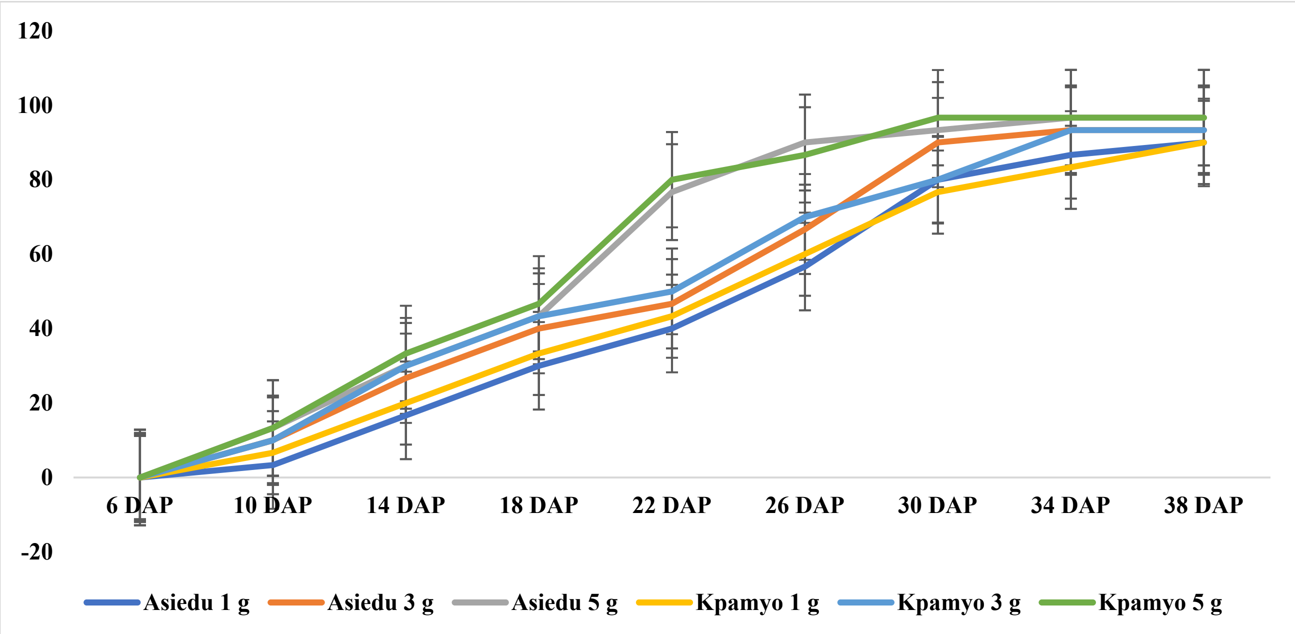

Figure 3. Combined number of days to emergence of minitubers of yam varieties Kpamyo and Asiedu over three years (2017–2019) in Abuja, Nigeria.

3.2. The Effect of Minituber Size and Variety on Yield and Related Traits

The 5 g minitubers had significantly longer vines, higher LAI, mean tuber weight (g) per stand, yield (t ha^{-1}), and more tubers per plant and per hectare, followed by the 3 g and then the 1 g minitubers (Table 1). At 3 MAP, the LAI of 5 g minitubers-derived plants (4.2) was 33% and 50%, more than 3 g and 1 g minitubers plants, respectively. Plants from the largest minitubers had significantly more leaves than those from smaller minitubers. The yield from 5 g minitubers (23.6 t ha^{-1}) was 39% and 25% more than those from 1 g and 3 g minitubers, respectively. Only the sett multiplication ratio had an inverse relationship, with the smallest minitubers having the highest value (138.1) compared to the 5 g and 3 g minitubers (48.1 and 58.6, respectively) (Table 1).

Table 1. Mean seed multiplication ratio, growth, and yield response variables of two *D. rotundata* Poir. varieties planted with 1, 3, and 5 g minitubers in Abuja, Nigeria during the 2017, 2018, and 2019 cropping seasons.

Factors		Days to 50% Emergence	Crop Establishment (%) at 8 WAP	Vine Length (cm)	Number of Leaves	Leaf Area Index	Yield (t ha^{-1})	Seed Multiplication Ratio	Mean Tuber Weight (g) Stand^{-1}	Mean Number Tubers Plant^{-1}	Tuber Number ha^{-1}
Minituber Size											
	1 g	23.8 b	90.4 a	135.2 a	68.3 a	2.1 a	14.4 a	138.1 b	159.2 a	1.1 a	101,296 a
	3 g	21.7 b	94.1 b	158.6 b	77.6 a	2.8 b	17.7 b	58.6 a	187.3 b	1.2 b	112,593 b
	5 g	18.8 a	94.6 b	186.9 c	105.4 b	4.2 c	23.6 c	48.1 a	249.4 c	1.4 c	130,556 c
	LSD	2.16	3.32	13.68	7.19	0.36	2.26	11.27	25.32	0.07	7231
Variety											
	Asiedu	21.6 a	92.6 a	158.1 a	86.4 a	2.9 a	18.3 a	78.5 a	195.8 a	1.2 a	113,457 a
	Kpamyo	21.4 a	93.5 a	162.3 a	81.2 a	3.2 b	18.9 a	84.7 a	201.5 a	1.2 a	116,173 a
	LSD	1.77	2.71	11.17	5.87	0.29	1.84	9.20	20.67	0.06	5904.1
Year											
	2017	22.2 a	90.9 a	160.5 a	89.8 b	3.1 a	14.9 a	69.6 a	164.6 a	1.3 b	114,444 ab
	2018	21.6 a	92.8 ab	159.0 a	82.8 ab	3.0 a	15.7 a	63.2 a	168.3 a	1.2 a	110,370 a
	2019	20.6 a	95.4 b	161.1 a	78.8 a	3.0 a	25.1 b	112.0 b	263.1 b	1.3 b	119,630 b
	LSD	2.16	3.32	13.68	7.19	0.36	2.26	11.27	25.32	0.07	7231

Means with the same letter along column are not significantly different at $p \leq 0.05$.

The analysis of variance for the yam varieties showed no significant differences for all the variables measured except for the LAI, where Kpamyo had a better performance than Asiedu. However, there were seasonal differences for some of the variables. For example, the number of days to 50% emergence, length of vine, and LAI were not significantly different across the years. In contrast, the crop establishment, yield, sett multiplication ratio, and the mean weight and number of tubers were substantially higher in 2019, perhaps due to the higher and more extended rainfall period. The mean weights of tubers produced were quite different, between 140.8 g (1 g) and 158.2 g (3 g) for the smaller minitubers and 181.8 g for the biggest (5 g). The number of tubers per plant was significantly more for the 5 g minitubers and least for the 1 g minitubers.

Significant interactions (Table 2) were found between and within minituber sizes, varieties, and cropping seasons for some measured variables. The percentage of crop establishment ranged from 87% to 97.8% across the years, and significant differences were observed between tuber sizes. Irrespective of the variety, 1 g minitubers were not significantly different in performance across the experiment years and had crop establishments ranging between 88.9% and 93.3%. The highest percentage of crop establishment was observed for 3 and 5 g minitubers of Asiedu and Kpamyo, respectively, in 2019. For the LAI of Asiedu and Kpamyo, 5 g minitubers had the highest value of 4.8 and 4.3, respectively, which were significantly different from the 1 g minitubers of both varieties with mean values of 2.0 and 1.6, respectively.

The yield parameters were observed to be significantly different among and between minituber sizes and varieties. The 5 g minitubers of Kpamyo obtained the highest yield of 31.2 t ha^{-1}. This yield was similar to 29.3 t ha^{-1} of Asiedu in 2019. The lowest yields were 10 and 10.2 t ha^{-1} from 1 g minitubers of Kpamyo and Asiedu, respectively, in 2018 (Table 2). Some 1 g minitubers gave comparable yields to 3 g and 5 g minitubers in 2019 when 1 g of Asiedu yielded 18.8 t ha^{-1}. This yield was slightly higher but not significantly different from Asiedu 3 g in 2017 (13.9 t ha^{-1}) and 2018 (15 t ha^{-1}), as well as 5 g Asiedu in 2017 (16.3 t ha^{-1}).

The mean number of tubers per plant ranged from 1.1 to 1.5, with the largest minitubers producing significantly more tubers than the smallest. The mean number of tubers produced per hectare by 1, 3, and 5 g minitubers was 101,296, 112,592, and 130,555, respectively. The highest mean tuber weight was obtained from 3 g (219 and 205.7 g) and 5 g (238.5 and 210.6 g) minitubers of Kpamyo and Asiedu, respectively, in 2019 (Table 2). On an individual tuber basis, the smallest tuber size produced ranged from 4 g obtained from 1 g minitubers of Asiedu to 14 g by 5 g minitubers of Kpamyo and Asiedu. In comparison, the maximum tuber weights ranged from 488 g (by 1 g minitubers of Kpamyo) to 1054 g (by 5 g minitubers of Asiedu). The SMR was between 35.1 and 213.8, being lowest for the 5 g minitubers and highest for 1 g minitubers. Irrespective of the variety and year, the 1 g minitubers had significantly higher SMR values ($p = \leq 0.05$) than 3 and 5 g minitubers, except for 3 g minitubers of Asiedu and Kpamyo in 2019 that was similar to 1 g of both varieties in 2018.

Table 2. All interactions for *D. rotundata* Poir. varieties planted in Abuja during the 2017, 2018, and 2019 seasons.

Sett Size	Variety	Year	Days to 50% Emergence	Crop Establishment (%)	Vine Length (m)	No. Leaves	Leaf Area Index	Yield (t ha^{-1})	Seed Multiplication Ratio	Mean Weight/Tuber (g)	Number of Tubers (t ha^{-1})
1 g	Asiedu	2017	21.3 a–g	91.1 abc	155 a–d	78 bc	2.7 b–e	11.3 ab	106.3 e	114.5 ab	97,778 ab
		2018	25.7 g	87.8 a	136.3 abc	69 b	2.1 abc	10.2 a	99.5 de	108.3 ab	94,444 a
		2019	24.3 d–g	91.1 abc	134 abc	76.7 bc	2 ab	18.8 cde	180.7 g	179.5 cde	104,444 abc
	Kpamyo	2017	23.7 c–g	88.9 ab	127 ab	71 b	2.2 abc	13.9 abc	134.7 f	131 abc	105,556 abc
		2018	24.7 efg	91.1 abc	133 abc	65.3 ab	1.9 ab	10 a	93.8 de	104.2 a	96,667 ab
		2019	23.3 b–g	92.2 abc	125.7 a	50 a	1.6 a	22.4 ef	213.8 h	207 def	108,889 abc
3 g	Asiedu	2017	22.7 b–g	92.2 abc	163.3 cde	79.7 bcd	2.5 bcd	13.9 abc	47.4 a	127.9 ab	110,000 abc
		2018	21.7 a–g	93.3 abc	151 a–d	91.7 cde	2.5 bcd	15 abc	49.8 ab	133.5 abc	111,111 abc
		2019	21.7 a–g	97.8 c	161.7 cd	74.7 bc	2.3 abc	23.6 ef	75.5 bcd	205.7 def	115,556 cde
	Kpamyo	2017	25.3 fg	88.9 ab	157 a–d	74.7 bc	2.9 c–f	15.8 bcd	56.6 abc	154.2 abc	106,667 abc
		2018	20 a–f	94.5 abc	160 bcd	70 b	3.6 fgh	12.3 ab	40.6 a	109 ab	113,333 bcd
		2019	19 abcd	97.8 c	158.3 a–d	75 bc	3.2 def	25.5 fg	81.5 cde	219.1 ef	118,889 c–f
5 g	Asiedu	2017	19.7 a–e	90 abc	163.3 cde	121.3 f	3.7 f–i	16.3 cd	35.1 a	123.9 ab	132,222 efg
		2018	18.7 abc	93.3 abc	177.7 def	95.7 de	3.5 efg	26 fgh	53.7 ab	223.1 ef	116,667 cde
		2019	18.3 ab	96.7 bc	180.3 def	91 cde	4.3 g–j	29.3 gh	58.3 abc	210.6 def	138,889 g
	Kpamyo	2017	20.7 a–g	94.5 abc	197.3 f	114.3 f	4.5 ij	18.2 cde	37.2 a	135.6 abc	134,444 fg
		2018	19 a–d	96.7 bc	196 ef	105 ef	4.4 hij	20.8 def	41.7 a	159.3 bcd	130,000 d–g
		2019	16.7 a	96.7 bc	206.7 f	105.3 ef	4.8 j	31.2 h	62.3 abc	238.5 f	131,111 efg
		LSD	5.3	8.12	33.51	17.62	0.87	5.53	27.6	51.33	17,712

Means with the same letter along column are not significantly different at $p \leq 0.05$.

At harvest, the tubers were sorted out into four categories (Figure 4). It was observed that 5 g minitubers of Kpamyo produced 18% and 40% of seed tubers in the range of 150 to 249 g and 250 to 500 g, respectively, while the 5 g minitubers of Asiedu produced 22% and 32% of these seed tuber sizes, respectively. The 1 g minitubers of both varieties and 3 g minitubers of Asiedu produced the most proportion of tubers in the category of <50–249 g, while the bigger minitubers produced more seed of more than 500 g. The 1 g minitubers of Asiedu did not have any tuber bigger than 500 g.

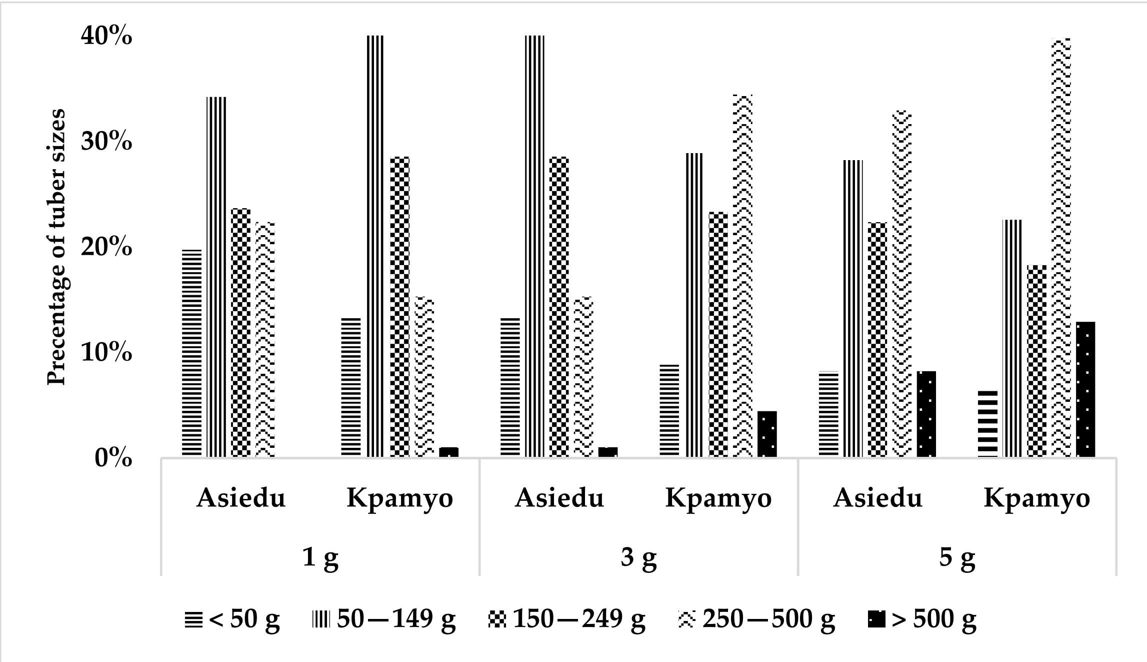

Figure 4. Percentage of various categories of tubers produced by different minituber sizes of yam varieties Kpamyo and Asiedu.

4. Discussion

4.1. The Effect of Minituber Size and Variety on Yield and Related Traits

For 2019 which presented the best yields, the 5 g minitubers had yields of up to 29.3 and 31.2 t ha^{-1} for Asiedu and Kpamyo, respectively. These yields are pretty high considering that in traditional practice, farmers plant seed tubers of 250–500 g and obtain less than 10 t ha^{-1} after 7–10 months, although at low plant populations of 6000 to 10,000 plants ha^{-1}. If we consider the mean values of 375 g of seed tuber planted at 8000 plants ha^{-1}, it translates to a seed rate of about 3000 kg ha^{-1}, compared to the 100–500 kg ha^{-1} of minitubers used in this study. An enormous quantity of tubers could be saved for food when this is extrapolated to Nigeria's entire yam-producing regions or that of West Africa.

In this study, three significant factors, among others, could be responsible for the exceptionally high yields despite the small size of the planting materials. Firstly, the type of sett planted (whole tuber against the cut setts that most farmers use) influences how fast plants emerged from the soil. Aighewi [25] observed that plants from whole tubers established faster and yielded more than tuber pieces (minisetts). The quicker the plants emerge, the longer the crop growth period, and the longer photosynthesis is performed and its products are produced and stored in the tuber to increase yield. Yam is predominantly cultivated as a rainfed crop, and senescence sets in 2–3 weeks after the rains stop irrespective of the tuber's size or maturity. This situation is in line with the study of Cornet et al. [26], who noted that the earlier plants emerge, the higher the tuber yield, regardless of weather conditions.

Despite the small size of tubers (0.1–5.99 g), between 87.8% and 97.8% of plants were fully established by 38 DAP (Table 2). Contrary to the extended period of emergence from the soil observed with larger cut setts, crop emergence and establishment was fast for this category of minitubers (Figure 5). A few days after emergence, the vines from the minitubers started producing leaves compared to the situation with bigger setts. In an ongoing experiment comparing the growth and yield of various categories of seed tuber sizes (tubers ranging from 10 to 250 g), it was observed that up to 25 DAP, there was an increase in vine length with an increase in the seed size. For example, the 10 g minitubers had a length of 82.3 $\pm$ 14.9 cm, while vines from the 250 g seed were 120.6 $\pm$ 35.2 cm. However, the mean number of opened leaves per stand for the 10 g seed tubers was 12 $\pm$ 3, whereas that of 250 g setts was 2 $\pm$ 4 (data not presented). This phenomenon suggests that when there is sufficient nutrient in the planted sett (as in the 250 g setts) to support initial plant growth, priority is on the vine's elongation. However, with limited stored nutrients (as in the 10 g minitubers), the plants become autotrophic sooner, and leaf production and expansion are accelerated to sustain plant growth and development. The early establishment with canopy production resulted in a longer crop duration, an extended period of nutrient accumulation in the tuber, and more yield.

Figure 5. Field planted with 1 g, 3 g, and 5 g minitubers at the International Institute of Tropical Agriculture, Abuja, Nigeria. Plants at three weeks after planting (WAP) (**left**), 5 WAP (**middle**), and 16 WAP (**right**).

From the spread of seed tuber sizes at harvest, the general trend was that the bigger the size of minitubers, the larger the seed tubers produced. Most farmers prefer to plant small whole tubers of 250–500 g, which were produced more by 3 g minitubers of Kpamyo and 5 g minitubers of both varieties used in the experiment. Some farmers may use setts of 150 g for small ware tubers, but setts smaller than this are mainly used to produce bigger seed tubers for the next season, or they are roasted and eaten as a snack. The large sett sizes utilized by farmers do not yield proportionately to the size planted due to poor quality. If 5 g minitubers can yield up to 23.6 t ha^{-1} after about five months in the field, compared to the average yield of 8.4 t ha^{-1} [1] of about 250 g seed after about eight months, it shows that the potential of the clean seed is high. Using virus-free seeds may require much smaller planting materials than the 250 g customarily used to produce average-sized yam tubers. Since the cost per seed yam is mainly determined by its size, smaller seed tubers will save cost for this most expensive input in yam production.

Secondly, the seed tubers used in this experiment were of good quality, obtained from virus-free plants of improved varieties grown in an aphid-proof screen house. Diehl [27] noted that the quality aspects of yam have two dimensions; getting the most suitable variety for a particular production situation and ensuring the integrity of cultivars in disease rating, the vigor of establishment, size, and type of sett. The virus-free whole tubers used were better able to demonstrate their potential by having an early crop establishment that eventually produced lush vegetation and high yields.

Lastly, planting was done at a high density of 100,000 plants ha^{-1} due to the seed tubers' small size. Even at the high plant population, it was observed that the interrow spacing of 1 m was too much since plants were staked and large portions of land were not covered by the foliage, allowing weeds to populate the area. Otoo [28] also observed that microsett populations could be as high as 250,000–444,000 ha^{-1}, and high densities could replace plastic mulch in the control of weeds. The yield from the pea-sized yam minitubers (Table 2) was a surprise. It far exceeded what was anticipated, especially in 2019, when the rainfall (Figure 1) was more than in the previous years (more than double the rainfall of 2017). Although there was not much difference in crop establishment between the minituber sizes, the largest seed (5 g) of both varieties had the longest vines, more leaves, highest LAI values, and eventually the best seed yam yields.

4.2. The Benefits of Using Minitubers for Seed Yam Production

The 3 and 5 g minitubers produced a mean tuber weight of 158.2 and 181.8 g, respectively, with an average of 112,592 and 130,555 seed tubers ha^{-1}, respectively (Table 1). Considering that the seed tubers produced are cleaner than farmer-saved seed in terms of virus infection, the sizes of seed tubers obtained could be used for ware yam production. With the current recommendation of planting 10,000 plants ha^{-1} for ware yam production, the number of tubers estimated to be produced per ha by the 3 and 5 g minitubers can plant 11 and 13 ha, respectively. In conventional practice, about one-third of the yield from one hectare is reserved for planting an equivalent land area as the one harvested [29]. Consequently, from a yield of 10 t ha^{-1}, about 3.3 tonnes will be reserved to plant another one hectare during the subsequent cropping season. However, if a system to produce and use minitubers for seed yam production is established, farmers may sell or use most of their ware yam for food and acquire planting materials from seed producers. Yam farmers mostly prefer the seed size produced by the 1, 3, and 5 g minitubers because they are planted whole with minimal cutting. Crops grown with whole seeds are more uniform in establishment and yield than those produced with a combination of whole and cut seed tubers, which is the customary practice [25].

Other advantages of using minitubers in seed yam production include reduction in bulk of the planting material, land preparation, and the possibility of mechanization. Transporting such small seed tubers would be less cumbersome. Planting was done on ridges, which are easier to prepare than the mounds used in conventional ware/seed yam production systems. Additionally, there is the possibility of adapting grain planters (e.g., maize, peanut, or soya bean) to plant the minitubers, many of which were similar to these grain sizes. The multiplication rate using minitubers at the onset of seed multiplication programs will be highly enhanced considering the SMR of 1:93.8–1:213.8 for the 1 g minitubers (Table 2) compared to 1:3 or 1:30 obtained using ordinary setts or minisetts, respectively. The technology to produce minitubers of less than 10 g is currently available [21,22,30], so the use of such tubers by seed programs should be encouraged to get improved and released varieties more readily available to yam farmers. The minitubers were found to behave like larger seed tubers in storage. Those used in this experiment were stored in brown paper envelopes to reduce dehydration and desiccation and stored in a well-aerated room with temperatures not exceeding 26 °C. They were in good condition for up to four months with about 3% loss, especially of the less than 1 g tubers. The storage loss was primarily observed after two months when dormancy was broken and occurring more within the fourth month of storage. This situation indicates that more extended storage as may be required by commercial seed yam producers would be possible if done in a more favorable environment such as in rooms with a temperature of 18 to 21 °C attainable with domestic air conditioners.

This study is the first to investigate the performance of high-quality minitubers of 0.1–5.99 g under field conditions. Consequently, further research is needed to determine the optimum agronomic management practices (appropriate plant density, as well as fertilizer, water, and storage requirements, among others) and production cost of this category of planting material for seed yam production.

5. Conclusions

Yam is a valuable tuber crop that enhances food security in West Africa, a region that produces 92% of the world crop. The crop is propagated conventionally with a portion of the tubers that would have been used for food. High-quality minitubers of 0.1 g to about 6 g (represented as 1, 3, and 5 g) of two improved and released yam varieties produced from vine cuttings of plants in an aeroponics system were planted in the field at 100,000 plants ha^{-1} to assess their potential in seed yam production. Results showed that for both varieties, the minitubers of 5 g emerged fastest from the soil (19 DAP) with crop establishment of 94.6% compared to the minitubers of 1 g that emerged from the ground at 24 DAP and had 90.4% establishment. The yields varied with variety, size of minituber, and cropping season, with the lowest yield of 10 t ha^{-1} obtained from 1 g minitubers of variety Kpamyo in 2018 and the highest yields, 31.2 t ha^{-1} from 5 g of Kpamyo in 2019. The very high SMR of up to 213.8 for the 1 g minitubers and the large number of sizeable seed tubers produced from the minitubers makes them suitable for inclusion in seed yam production programs.

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