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Developing commercial-scale fresh sweetpotato root storage in tropical areas of sub-Saharan Africa

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ABSTRACT

As food systems across sub-Saharan Africa transform and urbanise, demand for all-year-round supplies for the raw materials is increasing. This demand can be met through combinations of staggering crop production, purchasing from diverse geographical areas, and storing produce. Focusing on the increasing use of orange-fleshed sweetpotato root puree in vitamin-A-rich food products, we ran a series of storage trials in Kenya to investigate whether commercial-scale fresh orange-fleshed sweetpotato storage could provide a stable supply of roots for puree production. The trials studied storage of roots of two sweetpotato varieties (Kabode and Vita), using washed versus unwashed roots in wooden crates, and mains grid power versus off-grid solar-powered storerooms for four-months. Following curing at 30 °C, roots were stored at 20–23 °C, and quality assessed. After four months storage, 54–59 % (Kabode) and 63–83 % (Vita) of initial root weight remained suitable for processing into puree. However, weevil and sprouting problems occurred. Vita outperformed Kabode for most criteria. Neither root washing nor different storerooms had a consistent effect on root quality. Subsequent trials in a solar-powered store investigated if lower temperatures of ≤15 °C and 90 % rh, with pre-harvest dehaulming could reduce weevil development, sprouting and rotting in stored roots. While control of sprouting and weevil damage was achieved and dehaulming improved stored root quality, while washing reduced it, high incidence of rotting and root weight loss occurred. Increasing store ventilation did not reduce rotting. We conclude that further trials with well controlled storage environments are required to understand how raw root quality, dehaulming, harvesting and handling practices, curing conditions, air exchange, and packaging materials affect quality during fresh root storage.

1. Introduction

Urbanising food systems across sub-Saharan Africa (SSA) are driving rising demands for all-year-round supplies of raw materials in constant quantities and qualities. Orange-fleshed sweetpotato (OFSP) roots are increasingly being processed into products such as puree for producing vitamin-A-rich foods such as bread and chapatis in Kenya as well as in other SSA countries. Such agri-food supply chains will become ever more important across SSA in feeding the rapidly urbanising and increasingly nutritionally-aware population, but they face a wide range of risks. The pronounced seasonality of sweetpotato production and prices; adverse weather conditions; uncertain power supply; a labour force with limited food processing skills; and fluctuation in market demand particularly during the early stages of market development create many challenges. Staggered production, purchasing from different geographical areas, storage of fresh OFSP roots and combinations of these activities can help in mitigating these risks and achieving a stable all-year-round supply in terms of quantity and quality.

Most African countries spend millions annually importing wheat flour, particularly to serve their growing urban populations (Moyo et al.,

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2022). In 2022, the African continent spent an estimated 19.4 billion dollars on wheat importation (FAOSTAT, 2024). This leaves them highly vulnerable to global fluctuations in wheat prices, as demonstrated by the price shocks caused by the war in Ukraine in 2022. The economic profitability of puree substitution is driven by the relative prices of fresh sweetpotato roots and wheat flour in local markets (Low and van Jaarsveld, 2008), the cost of using different processing technologies, and in particular, the cost of packaging the puree (Moyo et al., 2022).

A study of the Kenyan sweetpotato value chain suggested the storage of fresh sweetpotato roots by puree processors for periods of up to four months could help mitigate these supply chain risks (Tedesco and Stathers, 2015). Large-scale producers cure and then store sweetpotato roots for up to nine months in sophisticated temperature-controlled purpose-built stores in the USA (Edmunds et al., 2008) and South Africa, and for much shorter periods and in small quantities in grass-covered and watered heaps by smaller-scale traders in Ghana. However, to our knowledge, no commercial-scale storage of fresh sweetpotato roots has yet been successfully managed in tropical areas of SSA. Our research set out to address this gap.

Sweetpotato roots often get damaged during harvesting or during the subsequent postharvest handling. However, sweetpotato roots retain the ability to heal their wounds after harvest through the process of curing. To cure sweetpotato roots, at the start of storage they are exposed to high humidity to prevent desiccation of the wounded tissues and warm temperatures to support active metabolism in the roots. The wound-healing process involves the synthesis of a layer of lignin to provide a barrier to water loss and entry of rot-causing pathogens, followed by the synthesis of a new periderm (skin) underneath this (Walter and Schadel, 1983; Ray and Balagopalan, 1997; Sowley and Oduro, 2002, cited in Ray et al., 2010; Holcroft, 2018). Curing results in reduced water loss, greater resistance to decay, and longer storage life (Holcroft, 2018).

Dehaulming is a process commonly used with root and tuber crops to help harden the skin of the root before harvest to reduce the injury and damage to roots that can occur during harvesting and handling. Dehaulming involves removing the above ground vegetative part of the plant several days prior to harvest. In studies in the USA, dehaulming was reported to reduce skinning injury to sweetpotato roots during harvesting by 62 % when the canopy was cut ten days before harvest, and by 26 % when cut four days before harvest (La Bonte and Wright, 1993). A study in Tanzania, found dehaulming significantly reduced the level of skinning injury in sweetpotato roots during harvesting and postharvest handling, and reduced the incidence of rotting in fresh roots (Tomlins et al., 2002).

Our research objectives were to: test the feasibility of maintaining the quality of fresh OFSP roots for processing into puree over a four-month storage period in a commercial-scale solar-powered store in a tropical area of sub-Saharan Africa; and to determine the main factors affecting the quality of freshly harvested OFSP roots during storage under these conditions. The effects of variety, curing and dehaulming, and washing or manually removing the dry soil from the roots were studied using a series of different store designs under a range of storage temperature and relative humidity (rh) conditions.

2. Materials and methods

A series of fresh sweetpotato storage trials (Trials 1, 2, 3, 4) were run. Learning from each trial was used to inform the design of the subsequent trials. The details of the trials; dates, stores used, postharvest treatments, curing conditions, storage environments are summarised in Table 1.

2.1. Sweetpotato root supply

Orange-fleshed sweetpotato (OFSP) roots were harvested by farmers from their fields in Kabondo sub-county, Homa Bay county, Kenya. Farmers providing roots for the trials had been given the OFSP planting materials and associated production training by the International Potato Centre (CIP) team based in Kisumu. The CIP team maintained regular communication with farmers in advance of the trials to ensure the roots could be purchased for the trial and harvested by ox-plough approximately four months after planting and on the exact date required for trial

Table 1
Treatments, curing and storage conditions for four sweetpotato storage trials.

Trial	Treatment	Store	Curing conditions	Storage conditions	Trial start date and duration	Notes
1	Vit-W-Solar Vit-UW-Solar Vit-W-Mains Vit-UW-Mains Kab-W-Solar Kab-UW-Solar Kab-W-Mains Kab-UW-Mains	Two rooms of a building converted into insulated temperature-controlled storerooms: Solar = off-grid solar-powered evaporatively cooled store Mains = mains grid-powered evaporatively cooled store	*Target*: 3–5 d at 30–32 °C and 95 % rh *Actual*: 5 d. Mains store temperatures >32 °C led to heaters being switched off at night Solar-powered store <30 °C. Temperature and rh fluctuated in both storerooms	*Target*: <20 °C and 90 % rh *Actual*: 20–23 °C and 86–96 % rh	November 13, 2016 *Target*: 4 m *Actual*: 4 m	60 wooden crates of Kab (15 for each treatment; 30 in each store) 50 wooden crates of Vit (12 crates of each treatment in solar store; 15 crates of each treatment in mains store) 35–40 kgs roots per crate n = 3 replicates/sampling
2	W-NH UW-NH W-DH UW-DH	Solar-powered air-conditioned store	*Target*: 5 d at 28–30 °C and 95 % rh *Actual*: during curing, temperature rose above 34 °C due to greater than anticipated heat production by roots, and a/c	*Target/Actual*: 15 °C and 85–90 % rh	October 02, 2017 *Target*: 4 m *Actual*: 3 m	81 wooden crates 16 crates of each treatment; plus extra crates of UW-NH and W-NH which would not be sampled 30–40 kgs roots per crate n = 4 replicates/sampling
3	W-NH UW-NH W-DH UW-DH	Solar-powered air-conditioned store	*Target*: 28 °C and 95 % rh for 4 d *Actual*: 28–29 °C and 90–95 % rh	*Target*: 15 °C and 85–90 % rh *Actual*: 13–15 °C and 90 % rh	February 19, 2018 *Target*: 4 m *Actual*: 4 m	81 wooden crates 16 crates of each treatment; plus extra crates of UW-NH and W-NH which would not be sampled 30–40 kgs roots per crate n = 4 replicates/sampling
4	UW-NH	Solar-powered air-conditioned store	*Target/Actual*: 28 °C and 95 % rh for 4 d	*Target/Actual*: 15 °C & 85–90%rh	November 21, 2018 *Target*: 4 m *Actual*: 2 m	81 wooden crates 30–40 kgs roots per crate n = 9 replicates/sampling

Key: Vit = Vita variety; Kab = Kabode variety; W = Washed roots; UW = Unwashed roots; Solar = off-grid solar powered store; Mains = Mains grid powered store; NH = normal harvest; DH = dehaulmed (foliage removed pre-harvest); OFSP = orange fleshed-sweetpotato.

set-up.

For Trial 1 two varieties, Kabode and Vita, were harvested. It was difficult to obtain three tonnes of undamaged Vita roots, so fewer crates of Vita roots than Kabode were placed in the stores, but there were sufficient crates for equal numbers to be sampled throughout the trial.

In subsequent trials (Trials 2, 3, 4), multiplication and dissemination of planting materials had been done by farmer multipliers and records had not been kept of which varieties had been distributed or planted beyond the fact that they were 'OFSP' varieties. As the two varieties were visually very similar, it was not possible to confirm the varietal identity from the foliage or root shape or colour, so all the roots were simply identified as OFSP roots. As farmers in the area preferred sharing cuttings of and growing Kabode, it was assumed that the majority of these OFSP roots were Kabode variety.

2.2. Harvesting and handling of roots prior to trial set up

The use of an ox-plough for the harvesting of sweetpotato roots is common in Kabondo sub-county of Kenya and this method was used for harvesting the roots for these trials (Fig. 1). Once roots became visible the team following the plough manually collected the roots using baskets, transferred them to the shade and then sorted them to remove any small, broken or weevil damaged roots. The sorted roots were then loaded into clean woven polypropylene sacks and transported in a covered truck to Organi Ltd., where the storage trials were housed. All roots were sorted again on arrival at Organi Ltd. prior to the trial set up, to remove any small, broken or weevil damaged roots that had been missed during the field sorting. Due to the number of roots required and the nascent stage of the OFSP market in the region, roots had to be harvested from up to nine fields to obtain sufficient quantities for each trial, and so for each variety the roots were mixed thoroughly to ensure randomisation.

The roots for each treatment replicate were packed in wooden crates (Fig. 2), which were sanitised a week before the start of storage by scrubbing with a 5 % bleach solution and drying in direct sunlight with regular turning. During trial set-up, prior to root loading, the empty wooden crates were weighed and labelled. Each crate was loaded with 35–40 kgs of roots (approximately 100 roots) for a single treatment replicate. The loaded crates were placed in the shade for several hours prior to recording the weight of each of them and placing them into the store according to the experimental design described further below.

2.3. Pre and postharvest treatments

2.3.1. Soil removal from roots

Two methods for removing soil from roots before storage were tested; root washing (W) and manual removal of dry soil from the roots (UW). For root washing a team of women at Organi Ltd., manually washed the roots as they moved them through a series of three large washing basins filled with tap water during which the soil was manually washed off them, and the roots were then rinsed clean. The roots were then sun-dried by placing them on the ground on large sheets, created by stitching together clean woven polypropylene sacking. The roots were turned over and moved at least twice during one to 2 h of drying to ensure that all of their surfaces were fully dry prior to loading into wooden crates.

2.3.2. Pre-harvest dehaulming

In Trials 2 and 3, the effect of manually dehaulming sweetpotato plants (removal of all above-ground foliage) prior to harvest on stored root quality was examined. In Trial 2, half the plants were dehaulmed three days prior to harvest. In Trial 3, half the plants were dehaulmed four days prior to harvest.

2.4. Store design

Trial 1 was set up using two storerooms at the Organi Ltd. sweetpotato processing plant in Ringa, Kadongo, Homa Bay county of Kenya (in the former Nyanza Province). Two rooms of the building were converted into plywood-lined insulated temperature-controlled storage rooms. The temperature controls in one storeroom were powered by solar and in the other by mains grid electricity. The insulated storerooms were equipped with heaters, charcoal-based evaporative coolers, and air circulation fans (further details are provided in Marchant, 2017).

A solar-powered environmentally controlled sweetpotato store was subsequently developed using a shipping container, a standard air conditioning unit, axial fans, and a water sprinkler (Fig. 3, Precoppe and Rees, 2018). To assure uniform temperature and relative humidity distribution the system was simulated using computational fluid dynamics and air guides were also added. This new storage unit was able to consistently maintain a temperature of 28 °C and relative humidity of 95 % during curing and a temperature of 15 °C and relative humidity of 85–90 % during storage. This new storage unit was used for Trials 2, 3 and 4. The built-in centrifugal fan within the SP AC storage unit ensured air circulation. Additionally, two axial fans were installed to pull air

Fig. 1. Ox-plough harvesting of sweetpotato in Kabondo (Photo: T. Stathers).

Fig. 2. Sweetpotato roots packed in wooden crates prior to loading them into the store (Photo: T. Stathers).

from below the crates, promoting consistent air movement. For aeration, the fans blow fresh air into the chamber, and vents allow exhaust air to exit, ensuring proper ventilation. Temperature control was managed through the air conditioner's sensor. A CoolBot device was used to enable the air conditioner's temperature sensor to reach the desired 15 °C during the storage phase. The CoolBot display was used to set the temperature. Humidity conditions were achieved through use of a water sprinkler system that sprayed at regular intervals. The spraying intervals were determined in pre-trials, using the Rotronic HygroClip to monitor temperature and rh.

2.5. *Curing and storage conditions*

2.5.1. *Curing*

During Trial 1, the heaters in the storerooms were switched on one day before store loading and water was sprinkled across the floor to raise the humidity in the two storerooms. The target curing conditions were three to 5 day at 30–32 °C and 95 % rh (Kushman and Wright, 1969). Clean sacks were placed over the tops of the upper-most boxes during curing to help retain high relative humidity and temperatures. These sacks were removed after the curing period and empty wooden crates were then placed on top to help prevent higher moisture loss.

Given the lack of knowledge regarding optimal curing times required for these two OFSP varieties, a physical examination of whether curing had occurred was done each day. It was not practical to follow the assessment of lignification by chemical staining method as used by van Oirschot et al. (2006) as it was not possible to obtain the chemical phloroglucinol. Instead, a two-stage visual observation method was used. Twelve additional roots of each treatment were placed in crates in the storerooms after small strips of the skin of these roots had been removed using a clean knife to create wounds. The two-stage visual observation method involved daily observation of the surface of the wound, and once a shiny layer had formed over the wound site, a section was then cut down into the wound site to check for visual signs of a thickened periderm. Previous experience by the research team indicated that it was possible to observe initial stages of curing by the formation of a shiny layer at the tissue surface, this was supported by the literature (Walter and Schadel, 1983; van Oirschot, 2000). While externally the root wound areas appeared to have cured after one to two days (having become sealed and slightly shiny), it took five days for the thickened periderm to form. At the point that cutting down into the wound site did not cause the sub-periderm layers to brown, the wound was considered to be completely healed (lack of browning indicates the loss of phenolics localised below the wound as a protective mechanism). Curing temperature and rh conditions were therefore maintained for five days, with active cooling then beginning on the sixth day.

In Trial 2, the targeted curing conditions were 5 day at 28–30 °C and 95 % rh ((Kays et al., 1992; Ray et al., 1994; Ravi et al., 1996 cited in Ray et al., 2010; Edmunds et al., 2008). While in Trials 3 and 4, curing was done for 4 day at 28 °C and 95 % rh.

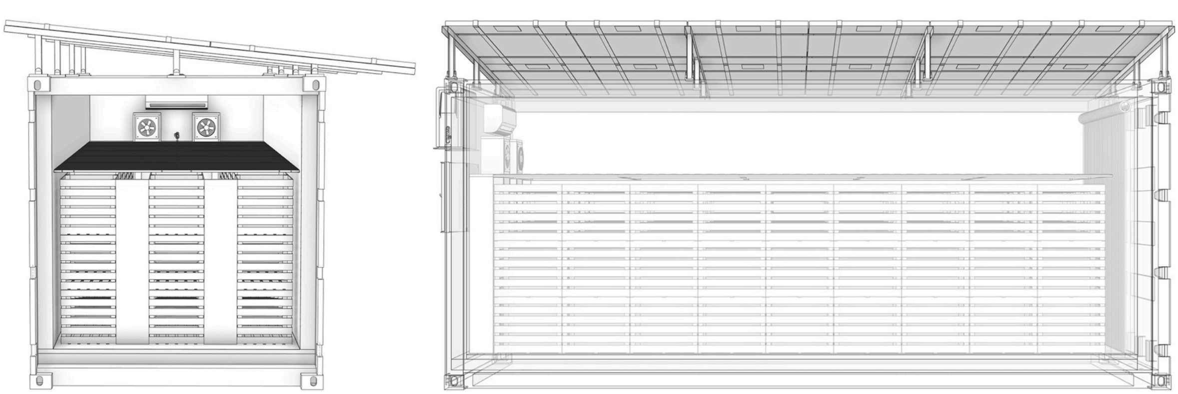

Fig. 3. (a) Front view of the solar-powered air-conditioned (SP AC) storage unit built inside a shipping container and (b) side view showing air conditioning unit, fans and photovoltaic panels (Source: Precoppe and Rees, 2018).

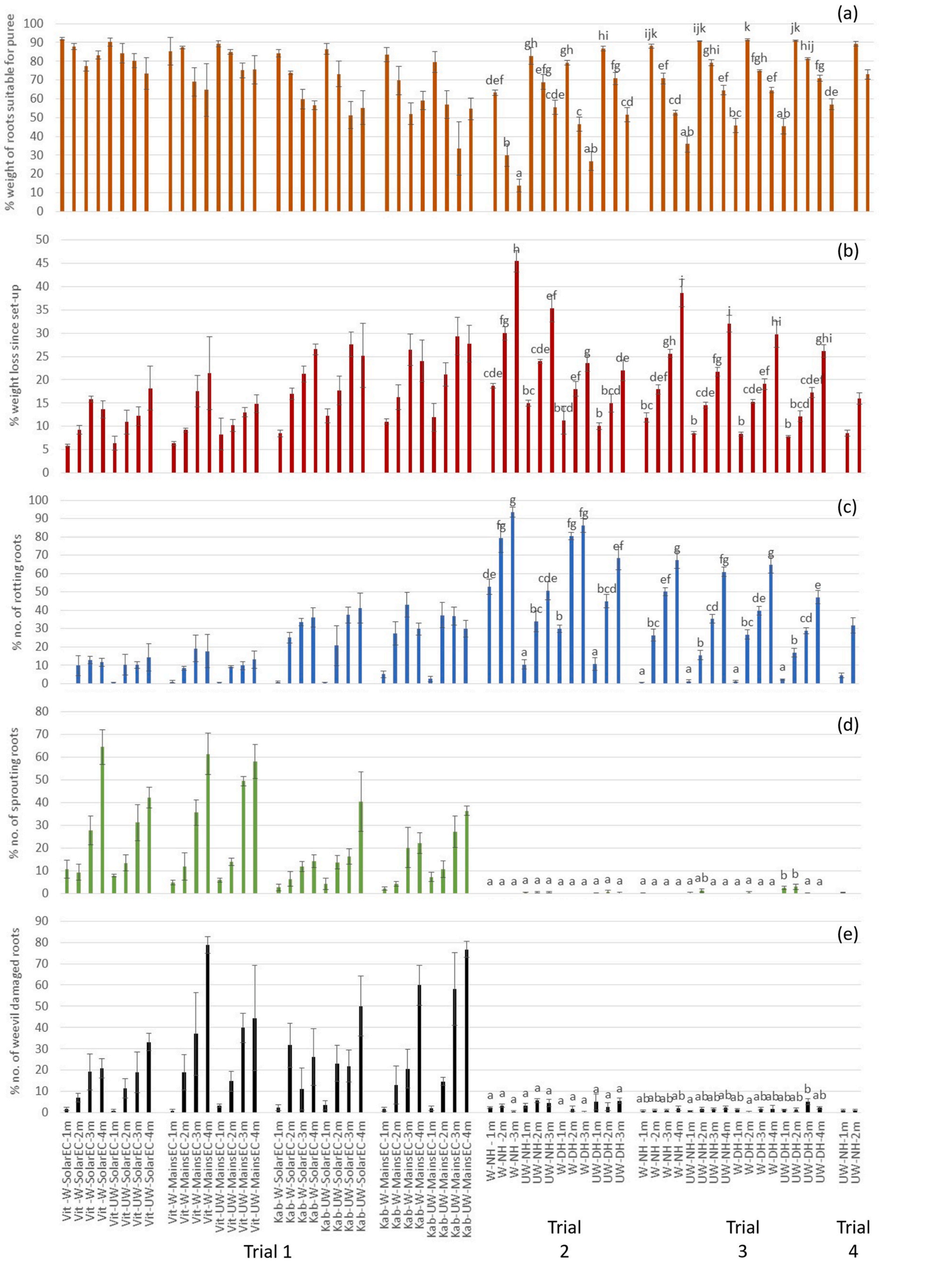

Fig. 4. Comparison of the mean percentage (±SEM) (a) weight of roots suitable for processing into puree relative to initial root weight, (b) weight loss of roots since set-up, (c) number of rotting roots per crate, (d) number of sprouting roots per crate, (e) number of weevil damaged roots per crate, at each monthly sampling (1m, 2m, 3m, 4m) for sweetpotato fresh root storage Trials 1, 2, 3, and 4. *(Vit=Vita, Kab=Kabode, W=Washed, UW=Unwashed, Solar-EC=Solar-powered evaporatively cooled store, MainsEC = Mains-powered evaporatively cooled store, NH= normal harvest, DH = dehaulmed). For Trials 2 and 3, within each trial, means followed by a different letter are significantly different ($p < 0.05$) using Tukey's test. Data for* 0 months *storage is not shown*

Table 2
Significance of different factors on aspects of sweetpotato fresh root quality during storage for the specified durations during Trials 1, 2 and 3.

Stored fresh root quality parameters	Trial 1 (analysis used aggregated data for 8–16 weeks of storage)				Trial 2 (0–3 months storage)							Trial 3 (0–4 months storage)						
	Factors				Factors			Interactions				Factors			Interactions			
	Variety	Washing	Power source (solar, grid)	Height level of crate in store	Storage months	Washing (W, UW)	Harvesting (NH, DH)	Mon*Wash	Mon*Harv	Wash*Harv	Mon*Wash*Harv	Storage months	Washing (W, UW)	Harvesting (NH, DH)	Mon*Wash	Mon*Harv	Wash*Harv	Mon*Wash*Harv
% weevil damaged roots (by number)			**			***	*	*				**						
% sprouting roots (by number)	***				**	***						***	***	***				
% roots with rots (by number)	***			***	***	***			**	**		***	***	**		**		
% weight loss	***			***	***	***	***					***	***	***				
% of initial root weight suitable for processing into puree	***		*	***	***	***	***	*		***		***	***	***				
% weight of discarded weevilled portion		*	**	*		***	***					**	*			**	*	
% weight of discarded rotten portion	***			**	***	***	***			***		***	***	***	*			
% roots with any signs of surface mould (by number)	*			**	***	***	**			*		***	***		**		*	
% roots with any defects (by number)					***	***		*	*	**		***	***		**	*		
General appearance score	***			*	***	***	*	**		*		***	***	**	*			
Sponginess score	***				***	***	**	*				***	***	*	***			
Shrivelling score	***				***	***	*	*		*		***	***	*				

Key: Significance codes: *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$. Mon = Months; Washing/Wash (Washed W; Unwashed UW); Harvesting/Harv (Normal Harvest (NH); De Haulmed (DH)).

2.5.2. Post-curing storage conditions

In Trial 1, following five days of curing, active evaporative cooling was begun to bring the storeroom temperature down to ≤20 °C. This included manually splashing water on the floor three times per day to maintain relative humidity at about 90 %. While in Trials 2, 3 and 4, following curing a lower storage temperature of 15 °C and ~90 % rh was targeted and this was achieved through programming of the control panel of the SP AC storage unit and no manual application of water was required.

2.5.3. Monitoring curing and storage conditions

A Rotronic HC2 hygrometer was used for monitoring temperature and rh. This equipment provides temperature accuracy of ±0.1 K, temperature resolution 0.1 °C, humidity accuracy ±0.5% RH and humidity resolution <1% RH. Two externally located temperature and rh displays enabled the conditions within the store to be monitored without opening it, allowing the operator to make adjustments to the CoolBot unit or water sprinkler system as needed to maintain target conditions. In addition during trials 2, 3, 4 a Rotronic CP11 datalogger was used to confirm temperature and rh as well as recording CO_2 concentration (range up to 10,000 ppm = 1%). The CP11 data logger was placed at the opposite end of the container from the doors. The battery for the logger lasted only a few days, and so was manually changed at regular intervals at which point the store was opened and well ventilated to bring CO_2 to near ambient and therefore allow safe entry.

2.6. Trial design

The different trials explored the effect of specific factors on maintaining the quality of freshly harvested OFSP roots during four months of storage as set out in Table 1.

Trial 1 aimed to understand the effect on stored root quality of a) variety (Kabode versus Vita), b) method of soil removal from roots (washed (W) versus unwashed (UW) manual removal of dry soil), c) store energy source (mains grid power versus off-grid solar power), and d) storage duration. During the analysis, we also examined whether the height (top, middle, lower) of the crate in the store influenced root quality during storage.

Trials 2 and 3 aimed to understand the effect of dehaulming versus normal harvesting and washing versus dry manual removal of soil from roots prior to storage for 4 months in the new off-grid solar-powered air-conditioned store. As described above, continued study of the effect of variety on root storage quality was not possible. Trial 4 aimed to understand the effect of increased airflow and ventilation within the off-grid solar-powered air-conditioned store on the quality of normally harvested unwashed OFSP roots for 4 months of storage, particularly regarding the incidence of rotting.

2.7. Experimental design

For Trial 1, following root sorting and set-up, 60 wooden crates each containing 35–40 kgs of Kabode roots were stored, these comprised 15 crates of each of the following treatments: Kab-W-Solar; Kab-W-Mains; Kab-UW-Solar; Kab-UW-Mains (see Table 1). Due to the lower availability of Vita roots, 50 wooden crates each containing 35–40 kgs of Vita roots were set up covering the following treatments: Vita-W-Solar (12 crates); Vit-W-Mains (12 crates); Vita-UW-Solar (13 crates); Vita-UW-Mains (13 crates). The treatments were laid out using a randomised block experimental design in both storerooms. Four rows of five crates stacked three crates high were arranged in each storeroom with sufficient space between the rows to lift out the necessary crates for sampling.

For Trials 2 and 3, following root sorting and set up, 81 wooden crates each containing 30–40 kgs of OFSP roots were stored. These comprised at least 16 crates of each of the following treatments: washed roots following normal harvesting (ox-plough method) (W-NH), unwashed roots and normal harvest (UW-NH), washed roots following dehaulming prior to harvest (W-DH), unwashed roots and dehaulming prior to harvest (UW-DH), the remaining crates would contain roots from whichever treatments there were most roots remaining of, which was usually UW-NH and W-NH treatments. Only 16 crates of each treatment would be sampled, the other crates were filled with roots to ensure the store contained the maximum volume of roots during curing and storage as it had been designed to provide stable curing and temperature conditions when fully loaded. A completely randomised block experimental design was used. Three rows of nine crates stacked three crates high were arranged with sufficient space between the rows to lift out the necessary crates for sampling. The design and sampling plan ensure four replicate crates of each treatment were sampled at each monthly sampling and then returned to the store, for each treatment one replicate was positioned in the top height level, another in the middle and another in the lower level and would be distributed across each of the three rows too. A further 16 crates (four of each treatment) were used for the baseline sampling and were never placed in the store.

For Trial 4, all 81 crates loaded into the store contained roots which had been normally harvested (UW-NH), and at each sampling a different set of nine replicate crates were assessed and then returned to the store. A randomised block design was used to create the sampling plan for selecting the nine replicates to be assessed. The nine replicates were distributed across the three height levels and three rows of the store. A further nine crates were used for the baseline sampling and were never placed in the store.

2.8. Sampling and data collection during trial

At set-up, the weight and number of roots were recorded for each crate, and then a detailed destructive assessment of three (Trial 1) or four (Trials 2 and 3) or nine (Trial 4) crates of each treatment was undertaken to provide baseline data for 0 months storage. After 1-, 2-, 3- and 4-months storage, a monthly assessment occurred. This involved downloading and checking the temperature and humidity data loggers and assessing the replicate crates per treatment per store. In Trial 1, three replicates per treatment were analysed at each sampling, while in Trial 2 and 3, four replicates per treatment were assessed and in Trial 4, nine replicates.

During the raw root assessment, the store was opened by at least two people, and the strip curtains were then opened to allow air to flow into the store for at least 2 min to reduce the risks of entering the store while CO_2 levels were high. Three crates were then removed from the store at a time for sampling. During Trial 1, the sampled crates were not returned to the store. While during Trials 2, 3 and 4, the sampled crates minus any weevilled or rotted discarded portions of roots were returned to the store after sampling to ensure the volume of roots in the store remained as stable as possible during the entire storage duration.

During each raw root sampling, the following criteria were sequentially assessed for each crate (treatment replicate) and the associated data was recorded.

- TOTAL ROOTS - weight, number, and photo
- GENERAL APPEARANCE SCORE (using a 1 to 9 scale, with 9 = best freshly-harvested looking roots)
- SPONGINESS SCORE (using a 1 to 9 scale, with 9 = best firm non-spongy roots)
- SHRIVELLING SCORE (using a 1 to 9 scale, with 9 = best non-shrivelled roots; 1 = totally shrivelled)
- UNDAMAGED ROOTS – number, weight, and photo
- DEFECTIVE ROOTS (e.g., any surface mould, sprouting, weevil damage, and/or rotting) – number, weight, and photo
- ROOTS WITH SURFACE MOULD – number, weight, and photo
- SPROUTING ROOTS – number, weight, and photo
- WEEVIL DAMAGED ROOTS – number, weight, and photo
- ROOTS WITH ROTS – number, weight, and photo

- DISCARDED WEEVIL PORTION OF ROOTS - weight
- DISCARDED ROTTEN PORTION OF ROOTS – weight

Puree processing quality criteria and beta-carotene concentrations were also assessed but are not included in this paper.

2.9. Data analysis

Data was entered and manipulated in MS Excel to provide basic calculations such as the percentage weight loss of each sample since set-up, percentage of roots showing signs of damage, and the means and standard errors of the different treatments at each sampling point. The further statistical analyses described below used R version 3.5.1 (Core Team R, 2018).

For Trial 1, due to the complex multi-factorial experimental design an analysis using all the data from 8 weeks storage onwards (e.g., 8, 13, 16 weeks), was performed using a Generalised Linear Model with a logit link and quasi-binomial errors. The resulting analysis of deviance showed which of the factors (variety, washing to remove soil before storage, solar or mains grid powered store, the height of crates in the store) significantly affected the various measurements made in relation to root quality during storage. An analysis of variance of the means for the different treatments (combining the data from week 8 storage onwards) followed by separation of the means to generate compact letter displays (clds) was done. The clds indicate the direction of the treatment's effects, although it should be noted that as clds are obtained from a one-way ANOVA using a dummy variate with all the treatment combinations, significant effects can be lost in the noise.

Trials 2 and 3 had identical treatments and were a simpler experimental design than Trial 1. Statistical analysis included a Generalised Linear Model with a logit link and quasi-binomial errors. The resulting analysis of deviance showed which factors (storage months, washing to remove soil before storage or not, dehaulming or normal harvest, and their interactions) significantly affected the various stored root quality parameters. Subsequent ANOVAs were performed to determine whether the height level or row positioning of the crates influenced the root quality measurements. Means for each treatment were separated using a Tukey's test and the clds were determined.

3. Results

3.1. Trial 1

Trial 1 found storage of fresh OFSP roots in a tropical area of sub-Saharan Africa could be achieved and be an effective way for processors, and possibly also traders, to extend their supply of OFSP roots into periods of the year when farmers' harvesting of sweetpotato roots was limited. Between 64.7 and 83.3 % of the initial root weight of the Vita variety was suitable for processing into puree after four months of storage. Although for the Kabode variety, the proportion of roots remaining suitable for processing into puree after four months of storage was lower, ranging from 54.7 to 59.2 % of the initial root weight (Fig. 4).

The percentage weight loss of roots during storage was significantly affected by both the variety and the height at which the crate was stacked in the store, but not by washing of the roots pre-storage nor by the different store rooms/power source (Table 2). At four months of storage, the mean percentage weight loss ranged from 13.6 to 21.4 % for the Vita roots, and from 24.0 to 27.8 % for the Kabode roots.

However, high levels of weevil-infested and damaged roots had occurred by four months of storage ranging from 20.9 to 50.1 % of roots in the solar-powered storeroom, to 44.5–78.7 % in the mains grid-powered storeroom. Many roots developed sprouts. Between 42.1-64.5 % and 14.3–40.4 % of Vita and Kabode roots per crate, respectively, had sprouts by four months of storage. Surface mould and rotting also increased with storage duration, a higher mean percentage of the Kabode roots had rots (29.8–41.2 %) by 4 months of storage than the Vita roots (11.7–17.7 %). In the absence of opportunities for laboratory analysis of the rots, a comparison of the visual symptoms to those shown by Cantwell and Suslow (2001), Sweetpotato DiagNotes (O'Sullivan et al., undated) and Gai et al. (2016), suggested a range of rots including those caused by *Fusarium* spp., *Rhizopus* and *Botryodiplodia* were present.

Based on the general appearance score, the 'freshly harvested' appearance of the crates of Kabode roots reduced faster than for Vita during storage whether washed or unwashed. Although by four months of storage, the general appearance scores of all treatments had reduced to 4.5 to 5.5 given some of the roots in the crates were exhibiting rots, weevil damage, sprouts, shrivelling and a general dullness to their appearance. Kabode roots exhibited more rapid and extensive shrivelling than Vita, there was a slight increase in sponginess of roots in the first month particularly in the unwashed Kabode roots, after which it did not deteriorate further.

Statistically, variety was the factor with the greatest effect on root rotting, sprouting, weight loss, proportion suitable for processing into pureeing and proportion discarded, and general appearance, sponginess, and shrivelling. The height at which the crate was located in the store also significantly affected stored root quality parameters, suggesting spatial differences in conditions within the storerooms existed. The mains grid-powered storeroom was associated with higher weevil damage and the associated proportion of roots discarded or retained, suggesting greater multiplication of weevils occurred during the trial in the mains grid-powered storeroom.

The target curing conditions in Trial 1 were three to 5 day at 30–32 °C and 95 % rh as recommended by Kushman and Wright (1969). In practice, it proved difficult to maintain a constant temperature of 30–32 °C in the converted storerooms at Organi. In the mains grid-powered store, the temperature increased beyond this and so the research team switched the heater off overnight. In the solar-powered store, the temperature rarely reached 30 °C and the heater went off each evening at about 5 p.m. due to insufficient battery capacity to run it once the sunlight reduced, it typically switched back on at about 7 a.m.

Fig. 5. Dehaulmed unwashed roots after (a) 2 months of storage, and (b) 4 months of storage during Trial 3 (Photos: B. Otieno & T. Stathers).

After five days of curing, active evaporative cooling was begun to try and bring the temperatures in the two storerooms down to ≤20 °C and water was manually splashed on the floor three times per day to keep rh at about 90 % rh. The actual storage temperatures achieved were 20–23 °C, and 86–96 % rh.

Due to the importance of achieving a more constant and controlled temperature and rh during curing and storage, including the ability to reach a lower target storage temperature of 15 °C and ~90 % rh and reduce rodent entry, weevil development, sprouting and rotting during root storage, a new solar-powered air-conditioned (SP AC) store was constructed in a shipping container at Organi Ltd. This new solar-powered store was designed to have the ability to attain the target curing conditions and maintain storage temperatures at ≥12.5 and ≤ 15 °C and 90–100 % rh as used in the USA for long-term storage of sweetpotato roots. The new solar-powered air-conditioned store was used for Trials 2, 3 and 4.

3.2. Trial 2

The targeted storage conditions of ≤15 °C and 90–100 % rh were achieved in the new insulated and temperature and rh controlled solar-powered air-conditioned container store (hereafter referred to as 'SP AC store' (Fig. 3)). While the problems of root sprouting, weevil damage and rodent attack seen in the earlier trials in the converted storerooms were almost eliminated (<0.8 %, <5.8 %, 0 % of roots affected by sprouting, weevils, and rodents, respectively for three months storage in Trial 2), root quality however still deteriorated substantially during storage (Fig. 4). The mean weight loss of roots ranged from 22.0 % in the dehaulmed unwashed (DH-UW) roots to 45.4 % in the normal-harvest washed (NH-W) roots after 3 months of storage, and the mean percentage weight of roots remaining suitable for processing into puree ranged from 55.5 % in the NH-UW roots to just 13.5 % in the NH-W roots. This was due to the high incidence of rotting which occurred, which ranged from a mean of 93.5 % of NH-W roots (by number) with rotting to 50.7 % NH-UW roots, as those parts of the roots affected by rot have to be discarded prior to processing into a puree. Few roots retained their marketable quality. The high incidence of rotting led to the decision to end the trial at three months storage, as opposed to continuing to 4 months storage. High CO_2 levels in the store suggested root respiration rates indicative of stress (see also description of Trial 3).

During Trial 2, the targeted curing conditions were 5 days at 28–30 °C and 95 % rh. However, during the curing stage, the temperature rose above 34 °C and was above 32 °C for 32 h, exceeding the recommended curing conditions of 28–30 °C and 95 % rh. This was due to greater than anticipated heat production by the roots and the air conditioner having been disabled to reduce energy usage.

Further analysis of variance confirmed that in contrast to Trial 1, neither the height level nor row position that the crates were placed in during Trial 2 in the new SP AC store had a significant effect on any of the storage root quality parameters being measured. This suggests spatial stability of temperature and rh conditions within the store, which concurred with the outputs of the data loggers.

3.3. Trial 3

With the assumption that the unexpectedly high incidence of rotting observed in Trial 2 was related to temperatures during curing having exceeded the target rates, a subsequent trial (Trial 3) was set up in the SP AC store using the same treatments as in Trial 2. During Trial 3, curing conditions were kept within the recommended temperature and rh ranges of 4 day at 28 °C and 95 % rh. Again, no, or extremely low incidence of sprouting, weevil damage and rodent attack of roots occurred during the four months storage duration (0 %, <2.5 %, 0 % of roots affected by sprouting, weevils, and rodents, respectively) (Fig. 4). Mean weight loss ranged from 26.2 % in the DH-UW roots to 38.6 % in the NH-W roots after 4 months of storage. The mean percentage weight of roots remaining suitable for processing into puree ranged from 57.1 % in the DH-UW roots to just 35.9 % in the NH-W roots. This was again due to the high incidence of mean percentage number of roots with rotting, which ranged from 67.3 % of NH-W roots to 47.2 % of DH-UW roots after four months storage (Fig. 5). Dehaulming and dry manual soil removal as opposed to washing to remove soil from the roots, had a positive effect on sprouting, rots, and weight loss.

As for Trial 2, further analysis of variance confirmed that neither the height level nor row position that the crates were placed at during Trial 3 in the SP AC store had a significant effect on any of the storage root quality parameters being measured, suggesting spatial stability of temperature and rh conditions within the store.

For both Trials 2 and 3, CO_2 concentrations measured by the CP11 datalogger indicated that CO_2 frequently rose above 10,000 ppm (1%) during both the curing stage and the subsequent storage period. This is consistent with root respiration rates at a level indicative of stress. The data logger battery was changed every few days, and therefore the store ventilated to bring the CO_2 down to ambient concentrations. This gave an opportunity to see the rate of CO_2 increase on each occasion. Extrapolation of rates of CO_2 increase indicated that CO_2 concentration was generally between 1 and 3%. This suggests that O_2 concentrations would not have been reduced below 18%.

3.4. Trial 4

High CO_2 readings inside the SP AC store during Trials 2 and 3 suggested root respiration rates indicative of stress, possibly as a direct result of the elevated CO_2. Physiological stress of storage roots tends to make them less resistant to rots. Therefore Trial 4 was set up with increased airflow and increased store ventilation to reduce CO_2 build up and alleviate root physiological damage that may have exacerbated the extensive rotting seen in Trials 2 and 3.

Due to the set-up of Trial 4 occurring during the rainy season a dehaulming (DH) treatment was not included, as dehaulmed roots can sprout while still in the soil if rains occur in the period between dehaulming and harvest. Nor was any washing of roots included either as the evidence from Trials 2 and 3 showed washed roots experienced higher weight loss and rotting than unwashed roots, although this relationship did not occur in Trial 1. During Trial 4, all 81 crates in the SP AC store were filled with NH-UW roots and biweekly sampling was done using nine replicate crates to track changes in root quality.

Again, no, or extremely low incidence of sprouting, weevil damage and rodent attack of roots occurred (0 %, <1.3 %, 0 % of roots affected by sprouting, weevils, and rodents, respectively) during the first two months of storage (Fig. 4). Mean weight loss of roots increased from 8.6 % at one month storage to 16.0 % at two months storage, with a mean percentage weight of roots remaining suitable for processing into a puree of 73.0 % by two months storage. Again, a high incidence of the mean percentage number of roots with rotting occurred, reaching 31.6 % by two months storage, which was more than double the incidence of 15.5 % which occurred in the same treatment NH-UW at two months storage during the previous trial, Trial 3. Due to the high incidence of rotting, the research team stopped Trial 4 at two months of storage.

4. Discussion

This series of commercial-scale trials of fresh OFSP root storage in a tropical area of sub-Saharan Africa highlighted the numerous challenges and complexities involved in the large-scale storage of fresh OFSP roots in this context. Given that freshly harvested sweetpotato roots are cured and stored at a commercial scale in countries such as the USA and South Africa, it was originally envisaged that if the recommended sweetpotato curing and storage temperature and rh conditions used in those commercial stores could be achieved, successful fresh sweetpotato root storage would be possible. However, as this series of trials shows we have not yet achieved successful storage of a sufficient proportion of the stored roots. Sharing and discussing these findings and the remaining challenges is valuable to inform learning and to help reduce or avoid these issues in future efforts to develop commercial-scale fresh sweetpotato root storage in tropical areas of SSA.

4.1. Harvesting and handling

In more mechanised sweetpotato farming systems such as those in the USA, following dehaulming, sweetpotato roots will be mechanically lifted from the soil and sorted in the field by labourers wearing cotton gloves to reduce risks of handling damage including fingernail scratches and to remove any soil and sort out defective roots as the roots pass along the conveyor belt of the harvesting rig. The sorted roots are then carefully placed into a large wooden storage crate/bin which when full is taken and stacked in the store. The roots are initially cured in the store, then stored until required for the market, at which point they will be sorted, washed, and treated with fungicide before drying and packing into branded cardboard boxes for dispatch (Edmunds et al., 2008).

By contrast, in our focal context in Kenya dehaulming is not typically practiced, and smallholder farmers harvest their sweetpotato crops using either manual labour and hoe-type tools or ox-ploughs depending on the scale of production, land slope, size and shape, soil type and resources available. Ox-plough harvesting saves time and labour and enables sufficient roots for store loading to be harvested on one day. The farm family and/or hired labourers walk alongside the ox-plough harvested ridges and pick up the sweetpotato roots and toss them across to a heap between the rows, leaving any rotten or small ones behind on the field. The heap of roots may then be moved into a shady spot at the edge of the field or covered *in situ* with vines. Depending on the volume being harvested, the roots will then be collected and loaded into baskets or woven polypropylene sacks to transport them — which often occurs by donkey or motorbike — to the homestead or market (Tedesco and Stathers, 2015).

Rough handling and subsequent damage of the sweetpotato roots can occur at numerous points along the chain from: physical wounding and bruising during harvest and aggregation of roots into heaps; rough sorting or packing of roots; overpacking of sacks and skin damage to root surfaces; bruising or skinning injury during rough transport; breakage during overloading of vehicles or during unloading; rough sorting and handling on arrival at the processors. Given the delicate nature of the skin of many sweetpotato varieties, skinning and other injuries can provide easy entry sites for microbial pathogens with tropical soils and surfaces being rich sources of fungi and bacteria. Additionally, bruise-type wounds are reported to heal slowly and irregularly in sweetpotato (Strider and McComb, 1958 cited in Aked, 2001).

Our trials spawned a storage trial in Mozambique, which used carefully harvested and handled research station-produced roots and lower levels of rotting during storage were experienced. This might indicate the importance of farmer training on careful handling at and after harvest. However, it is likely if sweetpotato roots are stored on a commercial scale they will have been harvested and handled by smallholder farmers using their typical practices and therefore storage of such roots will be the reality faced by processors and thus storage trials need to work with such roots.

4.2. Method of soil removal from roots

The soil type and weather conditions influence the amount of soil on the surface of the sweetpotato roots at harvest. In the fresh root sub-chain in Kenya, prior washing of roots to remove soil is now demanded in many of the larger market centres, while in others the colour of the soil remaining on the roots is viewed as evidence of the approximate location of production (Tedesco and Stathers, 2015).

To avoid storing large quantities of soil and adding contamination risks to the store, for the trials reported here the soil was removed from the roots prior to storage. This was done either by washing or by manual removal by rotating dry hands softly around the roots. Although during Trial 1 washing did not influence the level of sprouting, rotting or weight loss, in the subsequent Trials 2 and 3 it was seen to increase them. While in Trial 2, washing was negatively associated with weevil damage to roots suggesting that it was either easier to spot weevil oviposition sites on washed than unwashed roots and then remove them during the pre-trial sorting or that the washing or subsequent sun-drying process may have killed any weevil life-stages inside the roots.

Washing adds extra costs in terms of time, labour, and materials (water, sheeting etc.), but it also reduces the amount of washing required later in the process when the roots are about to be peeled and processed into a puree. A sweetpotato storage study in Israel (Afek et al., 1998), refers to their unpublished results where washing of sweetpotato roots after harvesting reduced the level of decay during storage, which they suggested was due to the removal or reduction of soilborne pathogens. The quality of the washing water is also likely to influence rotting.

4.3. Dehaulming

The high risk of and vulnerability to damage of tropical sweetpotato roots highlights the potential importance of curing and skin thickening/dehaulming processes prior to fresh root storage. Our study attempted to use both. Dehaulming sweetpotato plants 3–5 days prior to harvest was used to help the plants to heal wounds, protect roots against disease and further damage during harvesting and handling, reduce shrinkage and extend storage. Although dehaulming is a process commonly used with root and tuber crops in various locations across the world, it is not commonly practiced among smallholder sweetpotato farmers in Kenya. Given the risks to the farmer of dehaulming their crop prior to harvest, collection, and payment of roots, a great deal of trust is required between the purchaser and the farmer if dehaulming is to occur. However, our trials illustrated the benefits of dehaulming for stored roots in terms of reduced sprouting, rotting, weight loss, and increased proportion of roots remaining suitable for pureeing.

Work in Ghana found significant reductions in skinning injury, weight loss and decay incidence with longer dehaulming intervals (i.e., dehaulming 2 and 3 weeks prior to harvest) for all four of the varieties they studied (Sugri et al., 2019). They additionally recorded higher total soluble solids, β-carotene, α-amylase activity, and dry matter contents with longer dehaulming intervals. While work in Uganda found dehaulming three to five days prior to harvest, could prolong shelf-life of stored roots for up to 60 days, while dehaulming 14 days before harvest led to sprouting (Kyalo et al., 2016).

4.4. Curing

Curing was done by exposing the sorted roots to the recommended curing conditions of 28–30 °C and 95 % rh, and in Trial 1 the physical taking of slices of intentionally wounded test roots to assess whether curing had occurred. Other researchers have suggested that feeling the peel of the crop can be used to assess curing, i.e., if the peel is firmly attached and does not 'slip' when pressed sideways the root has cured (Kitinoja and Kader, 2015). A high incidence of rots occurred in Trial 2 when temperatures during curing went above those recommended. Work by Thompson and Scheuerman (1993) suggested higher temperatures of 35 °C during sweetpotato root curing stopped curing. In Trials 3 and 4, curing was done for 4 day at 28 °C and 95 % rh.

Curing at improper temperatures or rh can reduce quality during storage, and fluctuation of more than a few degrees Celsius during storage is reported to lead to premature breakdown of the sweetpotato root and excessive weight loss (Edmunds et al., 2008). Very high humidity will cause the formation of condensation on the walls and roof of the store, causing maintenance problems and wetting of bins and roots, which promotes decay (Edmunds et al., 2008).

Given the high temperatures and rh used during curing, the curing period may also provide ideal conditions for the development of microbial pathogens such as those which can cause rots during root storage. Soil temperature at harvest has also been reported to influence the degree of wound lignification and weight loss and rots during storage, with roots harvested at soil temperatures of 10–12 °C and 22–25 °C suffering greater weight loss and rots than roots harvested at 15–17 °C (Walter et al., 1989). In smaller scale household-level sweetpotato storage trials in Ghana, high losses occurred in traditional, pit or clamp stores by 28 days storage, and higher rotting occurred in roots cured for 14 as opposed to seven days in pit and clamp stores by 56 days storage (Tortoe et al., 2008).

In California, well-cured varieties of sweetpotato are reported to experience 1–2 % weight loss per month during storage, while uncured sweetpotato roots lose 1.5–4 % weight per month depending on their level of skin injury (Thompson and Scheuerman, 1993). The root weight loss rates experienced during Trial 1 were much higher. Thompson and Scheuerman (1993) suggest ideal conditions for storing sweetpotato roots are between 12.5 and 15.5 °C, however it was not possible to reach such cool storage temperatures in the converted storerooms at Organi Ltd.

Given the high incidence of root rotting in Trials 2, 3, and 4, further work to better understand optimal curing conditions for the roots of these tropical OFSP varieties is clearly needed. Smaller-scale experimentation with a range of different curing and storage temperature ranges and rh ranges would be informative for better understanding optimal curing and storage conditions for the focal varieties.

4.5. Root rotting during storage

The percentage of roots exhibiting rotting increased to unexpectedly high levels in Trials 2, 3 and 4 in comparison to Trial 1. The trials were conducted in different stores, Trial 1 was in the converted storerooms, while Trials 2, 3 and 4 were in the SP AC store. In Trial 1, two varieties of OFSP were compared, Vita and Kabode, and rotting was significantly lower in Vita roots than in Kabode. In the subsequent Trials 2, 3, and 4, it was not possible to determine which variety of OFSP was being harvested - although it was thought to be mainly Kabode - and for the trials, all roots were mixed to homogenise the effect of this uncertainty. However, the rotting levels in Trials 2, 3 and 4 were higher than for Kabode roots in Trial 1, suggesting there was an additional effect influencing the incidence of rotting, which might be linked to the curing or storage temperature and/or rh conditions, or to prior contamination of the wooden crates or store surfaces.

Sweetpotato extension materials from the USA describe how contaminated bins/crates and surfaces in stores and packhouses can remain contaminated from one year to the next, and how postharvest diseases account for the greatest losses in stored sweetpotato, and in extreme instances may lead to almost 100 % loss due to decay (Edmunds et al., 2008). The same document explains how very dry soil at harvest can increase skinning injury of roots and favour *Fusarium* root rot, while flooded soils can increase rots caused by various other microorganisms such as *Rhizopus* soft rot, bacterial soft rot, *Fusarium* root rot, and sour rot. Sweetpotato roots exposed to cold and heavy rains around harvest time are also reported to rot rapidly during storage (Kushman and Deonier, 1958; Nielson, 1965; Chew and Hernandez, 1978), and those left in the sun after harvest (Hayma, 1982).

It was beyond the resources of the current study to systematically identify the different rots infecting the roots. A simple comparison with descriptions and photographs from Sweetpotato DiagNotes (O'Sullivan et al., undated), Gai et al. (2016) and Cantwell and Suslow (2001) suggested *Rhizopus stolonifer*, *Plenodomus* spp., *Botryodiplodia* spp., *Fusarium* spp. and possibly some bacterial rot were present, all of which are commonly found in tropical soils. Spores from the rot-related fungi can easily contaminate equipment and sites and it is not simple to sanitise them. Identifying the causal microorganisms of the rots may help identify critical control points within the system where practice changes could be made to reduce contamination risks. In our trials, the wooden crates were scrubbed clean with diluted bleach and sun-dried prior to each trial. Cleaning and sanitation of sweetpotato storage bins is recommended after each use (Edmunds et al., 2008).

For storage of crops such as pears, steam cleaning of wooden crates was found to be the most effective method of reducing populations of fungi, chlorine and ammonium compounds were also effective but less so than steam (Spotts and Cervantes, 1994). Sodium hypochlorite (bleach) was found to be less effective on wooden than plastic crates (Edmunds et al., 2008), suggesting it could be useful to study fresh root storage in plastic versus wooden crates. Wooden as opposed to plastic crates had been selected for our trials due to their price, local availability, durability and ease of repair. Leaving the wooden bins outside in direct sunlight is also thought to help reduce microbial contamination (Edmunds et al., 2008).

Fungicide application pre or postharvest may also help reduce rotting, although the original intention for our system was to store OFSP roots without the use of chemical pesticides which may have environmental and health, as well as cost impacts. As far as we currently understand, the OFSP roots stored in the USA do not have fungicide applied to them prior to curing or storage, although fungicide is commonly used after roots have been stored and are being graded and packed for transfer to market (Edmunds et al., 2008). However, in commercial operations in South Africa, roots are washed, dipped in a fungicide, and

Fig. 6. *Cylas* spp. weevil punctures on a freshly harvested sweetpotato root (Photo: T. Stathers).

then air-dried prior to curing. UV irradiation has also been shown to significantly reduce the percentage of stored sweetpotato roots that developed rots during a four-month trial in the USA (Stevens et al., 1990). The same study also highlighted how some varieties experienced higher rotting than others during storage (for example, Georgia Jet experienced more rotting than Jewel or Carver varieties), and how UV was effective against *Rhizopus* soft rot and *Fusarium* rot, while the fungicide Botran was effective against soft rot but not *Fusarium* rot. It has been suggested that varieties with low dry matter content are more susceptible to pathogens during storage, i.e., Jewel and Beauregard versus Georgia Jet, and that curing proved ineffective in protecting Georgia Jet from rots (Afek et al., 1998). However, in trials in Israel, when Georgia Jet variety roots were treated with the fungicide Iprodione and then cured, dry rots (later identified as *Fusarium*) occurred on 5 % of roots and soft decay (later identified as *Rhizopus*) on 9 % of roots after five months storage, versus 26 % and 35 %, respectively for roots that were only cured before storage, and 32 % and 68 %, respectively for roots which were not cured before storage (Afek et al., 1998). The Afek et al. (1998) study also compared three methods of applying the fungicide – dipping, spraying and fogging – and found no differences in effectiveness between them. Although Afek et al. (1998) suggested the 'dry cloud' containing disinfectant produced by the fogging method which prevented the roots from becoming wet during treatment was potentially beneficial for root quality. The biocontrol potential of *Trichoderma harzianum* strains for fungal pathogens of stored sweetpotato roots is being studied in South Korea (Paul et al., 2021). A recent review by Liu et al. (2023) compares the advantages and disadvantages of a range of different measures (e.g., physical curing and storage techniques and conditions; chemical fungicide sprays and dips; biological control antagonist microbes or chitosan, oligochitosan or chitinase coatings; essential oils) for control of the postharvest fungus *Ceratocystis fimbriata* during postharvest sweetpotato root storage.

High CO_2 levels indicative of high respiration rates and physiological stress in the stored roots were observed in Trials 2 and 3. On the basis that the high CO2 may have exacerbated the physiological stress Trial 4 was set up with increased airflow and store ventilation to help reduce CO_2 build up, and alleviate root physiological damage that may have exacerbated the rotting. Increased air movement and ventilation can not only reduce CO_2 but can also provide a greater opportunity for heat transfer important during curing, cooling, and removing the heat of respiration throughout the storage period (Edmunds et al., 2008). However, high levels of rotting still occurred in Trial 4.

Additionally, chilling injury at temperatures below 8 °C is reportedly expressed as rapid deterioration of the tissue and decay of the roots caused, mainly by the fungi *Rhizopus* spp. and *Fusarium* spp (Clark, 1992; Clark and Moyer, 1998) or *Penicillium* spp. (Edmunds et al., 2008). Others suggest chilling injury can occur below 10 °C (Edmunds et al., 2008), and that at temperatures below 9 °C roots become more susceptible to rotting by fungi due to modification of the cell wall structure and effects on the production of the phytoalexin ipomeamarone defence mechanism (Arinze and Smith, 1982). It is likely that different varieties experience chilling injury at different temperature thresholds, possibly even within the temperature range used in these trials. Further experimentation with different curing and storage temperature ranges and rh ranges using freshly harvested roots harvested during different weather conditions, could also be informative for identifying optimal conditions for these varieties.

4.6. Weevil damage during storage

The weevils, *Cylas puncticollis* and *Cylas brunneus*, are a major pest across many sweetpotato producing areas. The weevil-damaged portions of roots are viewed as unattractive and unpalatable and are sliced off before the sweetpotato roots are cooked and consumed. Sweetpotato root attack by weevils and fungi has been shown by Wamalwa et al. (2015) to elicit the production of furanoterpenoids, such as the toxic ipomeamarone, in the roots at distances of up to 2–3 cm from the visually damaged root area. This underscores the need for careful removal of both the infested and surrounding areas of sweetpotato roots before consumption and prevention of the damaged portions being fed to livestock.

Where temperature conditions are inducive, weevils (in their egg, larva, pupa or adult life stage forms) can continue to develop if already infested sweetpotato roots are placed in stores. This highlights the need for checking freshly harvested roots for weevil damage prior to loading them into stores, involving not only the removal of any roots with visibly heavily weevil-damaged areas but also the removal of any roots with even a pin-prick-sized oviposition site (see Fig. 6). An oviposition site may indicate the presence of an egg inside the root which could over a few weeks develop into an adult. Inspection for any oviposition sites requires careful checking, which adds further time and costs to fresh sweetpotato root storage.

As for most insects, the development of the *Cylas* spp. weevils which damage sweetpotato plants and roots is temperature dependent. A controlled study in Uganda reported 100 % egg mortality and no development and reproduction of *C. brunneus* at 15 or at 40 °C (Musana et al., 2013). Similarly, Okonya et al. (2017) found *C. puncticollis* - the species which is commonly found attacking sweetpotato in Western Kenya - did not develop at 16 °C, which confirmed earlier findings by Nteletsana et al. (2001). While by contrast *Cylas formicarius* — which is not found in Africa — was reported to thrive at 15 °C (Mullen, 1981), but became motionless at temperatures <13 °C (Sugimoto et al., 1996). However, subsequent research has shown *C. formicarius* can rapidly become cold–tolerant (e.g., survived 0 °C and −3 °C) through short periods of cold acclimatization at 15 °C (Kandori et al., 2006). This suggests any weevils that did develop into adults in stores maintained at 15 °C might over time become more adept at surviving and breeding at temperatures of 15 °C or lower.

In the USA, *C. formicarius* is the most serious sweetpotato pest nationally but is not found in North Carolina which is the top sweetpotato producing state in the USA. Given the severity of the pest, North Carolina state has invested in risk assessment, prevention, field and store monitoring, root treatments and supporting legislation to reduce the risk of even a single mated pair of sweetpotato weevils escaping and establishing through commercial shipments or illegal movements of sweetpotato plants, vines or roots including ornamentals in the morning glory family (Nilake, 1991; Addo-Bediako et al., 2007; Adams, 2018). This highlights the risks and the challenges of farming or storing sweetpotato in locations where *Cylas* spp. weevils are present.

By storing the roots at a lower temperature of <15 °C, we managed to successfully reduce the development of weevil life stages remaining in the roots.

4.7. Varietal effect on root storage

Trial 1 clearly illustrated how variety can affect root storage quality. As explained earlier, due to farmers subsequently taking over the multiplication and distribution of OFSP planting materials around the trial area and not keeping records of which varieties they had planted beyond them being OFSP, it was not possible to continue studying the varietal effect in our subsequent trials. Discussion with the head of sweetpotato breeding, Craig Yencho of North Carolina State University, USA revealed that breeding and selection of sweetpotato varieties in the USA include storage quality characteristics such as postharvest disease tolerance, skin thickness and shape, in addition, to yield and field disease tolerance. Postharvest storage related characteristics have not yet been a major feature of sweetpotato breeding programmes in Africa.

4.8. Commercial value of sweetpotato storage

Although our work was focused on the storage of OFSP roots for processing into a puree, it could also be of use to farmers or traders wishing to store fresh roots for targeting either the domestic or export fresh root market during times of low supply when prices are typically high. A study of the Kenyan sweetpotato value chain in 2015, found the peak and low supply season buying price for freshly harvested local yellow or cream flesh coloured sweetpotato roots varied between 20 % and 67 % in Kabondo, Migori and Busia counties while the percentage variation of the selling price was lower, e.g., 5 %–29 % (Tedesco and Stathers, 2015). However, as Tedesco and Stathers (2015) highlight, the economics of fresh root storage are not only dependent on the cost of storage and potential inter-seasonal buying price variation, but also on the retention of root quality during storage and intended use, and the proportion of purchased roots fit for storage (i.e., with no damage or rots).

Many of the quality characteristics we recorded data on are relevant for fresh root marketing, and work with consumers in the Kisumu market revealed they would be happy to purchase the high-quality sweetpotato roots that had been stored for three to four months based on their visual appearance. Other research highlights how the share of 'imported' food in the rapidly growing African urban middle-class diet does not rise with income, instead more meat and other locally produced and often perishable products (e.g. fresh fruits, fish and eggs) start to be eaten instead of imported wheat and rice (Tschirley et al., 2015). In East and southern Africa, the middle class ($2–20/day PPP) is projected to increase from 27 % of the population in 2010 to over 75 % by 2040, driving demand for increased logistics, cold storage, processing, wholesale markets, and retail services (Tschirley et al., 2015).

4.9. Remaining knowledge gaps, challenges and opportunities for further exploration

Clearly, many aspects of commercial-scale storage of fresh OFSP roots in tropical areas of sub-Saharan Africa need substantial further study and can build on the findings of our initial and novel work. While it was originally assumed that the sweetpotato curing and storage conditions used commercially in the USA could be adopted, in fact these conditions need further study to identify the optimal conditions for curing and storage of these tropical varieties of sweetpotato grown and handled under diverse smallholder systems which differ significantly in numerous ways from those in the USA. Further exploration using smaller-scale closely monitored studies to better understand the influence of the range of and combinations of the following aspects on fresh sweetpotato root storage is required: i) different curing and storage conditions, ii) different sweetpotato varieties grown in Africa, iii) different sizes and shapes of roots, iv) different raw root qualities, v) different harvesting (including dehaulming) and handling practices, vi) different packaging materials, i.e., plastic vs. wooden crates, vii) different store and crate sanitation practices, viii) different airflow and ventilation rates inside the store and ix) different pre and postharvest fungicides (including a range of products, application rates, methods and timings).

Ideally, these studies should be conducted close to the root production sites to reduce the need for extra handling, transport and delay between harvest and curing, all of which can cause root damage and deterioration of freshly harvested sweetpotato roots. No suitable controlled temperature and rh chambers were available for such studies in western Kenya during our trials. Small trials experimenting with different air flow rates on root quality are being conducted in the UK, using imported already cured and stored sweetpotato roots.

Despite the numerous challenges encountered, there were also achievements, including the development of: sweetpotato harvest and postharvest handling protocols and extension materials for use by OFSP processors and smallholder farmers (e.g., Stathers et al., 2019); rigorous protocols for analysing different dimensions of the quality of fresh sweetpotato roots during storage and puree production; a SP AC store with controlled temperature and rh conditions (see Precoppe and Rees, 2018 for further information); and the successful 4-month storage of a proportion of the OFSP roots for processing into puree.

Since these trials in Kenya, the processing company Organi Ltd. relocated and is not currently storing any of the OFSP roots they process. However, one of the trial team members is now the quality manager of a small private enterprise starting to export roots of both OFSP and the locally more commonly consumed yellow-fleshed sweetpotato from western Kenya to Europe. This nascent company is applying the dehaulming, root handling and sorting practices developed during our trials, and is continuing to set up small experiments involving different varieties, different curing, and storage conditions, different fungicides, and application regimes (although there are challenges with local access to fungicides approved for use in organic systems), and better control of temperature and rh conditions during sea freight. They are also working with farmers on understanding the currently high percentage rejection of roots at harvest due to quality aspects such as high incidence of weevil-related and handling damage and small size of roots. This ongoing learning and practice can feed into fresh sweetpotato root storage systems for the growing domestic as well as export sweetpotato value chains and for the different varieties dominating them.

5. Conclusions

Food systems across SSA are transforming in response to rapid urbanisation and changing socio-demographics and dietary trends. This leads to demand for all-year-round constant quantity and quality supply of food products. The current study was focused on exploring and developing commercial-scale storage of freshly harvested OFSP roots for four-month storage durations. These roots could then provide a steady supply of OFSP roots for the continuous processing into vitamin-A rich sweetpotato puree for inclusion in bakery product lines produced by supermarkets. Through a series of four consecutive storage trials of smallholder farmer produced OFSP roots, the storage for periods of four months of fresh OFSP roots which remain suitable for processing into puree was shown to be feasible. However, the proportion of roots which remained suitable for processing into puree was not high enough and varied by variety, harvesting method (normal vs. dehaulming) and trial. In the initial store and trial (Trial 1), curing and storage temperature and rh conditions were difficult to control and a high incidence of both weevil damage and sprouting of stored roots occurred. Using a purpose built solar-powered air-conditioned (SP AC) shipping container store, cooler and more controlled storage temperatures of 15 °C were achieved in subsequent trials and this led to reduced weevil damage and sprouting, but persistently high and increasing levels of root rotting transpired. This was despite experimentation with different harvesting (i.e., normal vs. dehaulming), handling (i.e., washing vs. unwashed roots), curing, air flow and ventilation practices. Further exploration using smaller-scale studies is needed to better understand the multiple factors influencing the quality of stored fresh sweetpotato roots grown in tropical areas of SSA. These studies should deepen understanding of the effect of different curing and storage conditions, varieties, root sizes and shapes, raw root qualities, harvesting and handling practices, packaging materials during storage, storage and crate sanitation practices, in-store airflow and ventilation rates, and pre and postharvest fungicide treatments.

CRediT authorship contribution statement

Tanya Stathers: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Benard Otieno:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Bethwel Kipkoech:** Writing – review & editing, Project administration, Methodology, Investigation. **Debbie Rees:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Marcelo Precoppe:** Writing – review & editing, Visualization, Software, Methodology, Investigation, Conceptualization.

Penina Muoki: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Jan Low:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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