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Underground Storage Organs

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I. INTRODUCTION

The vegetables for which the edible portion is an underground storage organ are commonly referred to as "root vegetables." This is actually a much more morphologically diverse group than is suggested by that term (Table 1). Although the edible portion of some of these vegetables is in fact a swollen tap root [e.g., beet, *Beta vulgaris* L. ssp. *vulgaris*, carrot, *Daucus carota* L., jicama, *Pachyrhizus erosus* (L.) Urban, parsnip, *Pastinaca sativa* L., turnip, *Brassica rapa* L. Rapifera Group], even among those, more or less of the edible tissue may also be hypocotyl tissue (e.g., beet, radish, *Raphanus sativus* L. Radicula Group). Cassava (*Manihot esculenta* L.) and sweet potato [*Ipomoea batatas* (L.) Poir.] are storage roots. Some of these vegetables, however, are actually underground stems: potato (*Solanum tuberosum* L.) and yam (*Dioscorea* spp.) are tubers (fleshy underground stems with buds or "eyes" in the axil of leaf scars); horseradish [*Armoracia rusticana* P. Gaertn. stn. *Nasturtium armonracia* (L.) Fries] and ginger (*Zingiber officinale* Roscoe) are rhizomes (elongated, horizontal underground stems); and taro [*Colocasia esculenta* (L.) Schott], malanga (*Xanthosoma* spp.), and waterchestnut [*Eleocharis dulcis* (Burm.) Trin. ex Hens.] are corms (short, thick, more or less upright, underground stems). The edible portion of onion (*Allium cepa* L.) and garlic (*Allium sativum* L.) bulbs is even further removed from the root, being comprised of enlarged, fleshy leaf bases.

The underground storage organs are also the most taxonomically diverse group of vegetables, representing more than a dozen different families, including both monocots and dicots (Table 2). The geographical origins of these vegetables are worldwide (Yamaguchi, 1983). The temperate-zone crops in this group (Table 1) are all best stored at near 0°C, while the tropical root crops are mostly best stored near 12–13°C (Table 3) due to their sensitivity to chilling injury (CI; see Chapter 16). Cassava is an exception among

Table 1 Classification of Underground Storage Organ Vegetables on the Basis of Their Origin and Primary Edible Plant Part

I. Temperate
   A. Roots (taproots and/or hypocotyl)—beet, carrot, celeriac, parsnip, radish, rutabaga, turnip
   B. Tubers (underground stems)—Jerusalem artichoke
   C. Bulbs (leaf bases)—garlic, onion, shallot
   D. Corms (underground stems)—waterchestnut
   E. Rhizomes (underground stems)—horseradish

II. Subtropical and tropical
   A. Roots—cassava, manioc, or yucca, and sweet potato (storage root), jicama or yam bean (taproot)
   B. Tubers (underground stems)—potato, yam
   C. Corms (underground stems)—malanga, tannia, or yautia, taro or dasheen
   D. Rhizomes (underground stems)—ginger

the tropicals, being best stored at 0–5°C, apparently because the physiological disorder "vascular streaking" makes the roots so greatly perishable at higher temperatures (Montaldo, 1973) and the fact that they are usually cooked immediately after removal from storage, which largely precludes development of CI symptoms. Potato is a subtropical crop best stored at 4°C to avoid CI symptoms (Table 3), but is often stored at higher temperature to avoid the conversion of starch to sugar that occurs below about 10°C, which makes the tubers unacceptable for processing. (See below.)

Many of these vegetables, such as cassava, potato, sweet potato, and taro, accumulate dry matter, usually starch, in the storage organ, making them important staple crops and sources of calories (Table 4) in the diets of many countries. Conversely, the water content of most of these crops is fairly low compared to many other vegetables, implying that their tissues are less succulent and somewhat less sensitive to mechanical damage compared with fruit vegetables or leafy crops. They are generally modest providers of protein in the human diet and are low in fat, but are good sources of vitamins and minerals. Carrots and orange-flesh sweet potatoes have extremely high levels of β-carotene (provitamin A), and cassava, jicama, potato, radish, rutabaga (*Brassica napus* L. Neobrassica Group), sweet potato, and turnip are all relatively good sources of vitamin C. For those vegetables in this group that are consumed as staple crops, the resulting high per capita consumption means that they can be very important dietary sources of nutrients. For example, Burton (1982) illustrated that while potato contains only about one-third or less the vitamin C per unit edible portion of orange [*Citrus sinensis* (L.) Osbeck], it accounts for three times the intake of that vitamin in the United Kingdom—35% of the total per capita intake.

The underground storage organ vegetables are subject to a number of physiological disorders. For those crops that originated in subtropical or tropical areas of the world, the most significant of these disorders is CI because of how it limits the ability of postharvest technologists to fully utilize temperature management to maintain product quality. General symptoms of CI in underground storage organs include internal discoloration and tissue breakdown followed by water loss (shriveling) and decay (Table 3). Both potato tubers and parsnip roots exhibit conversion of starch to sugar at low temperatures ("low temperature

Table 2 Taxonomic Classification of Some Underground Storage Organ Vegetables

Common name	Genus and species
Dicots	
Chenopodiaceae	
Beet	*Beta vulgaris* L. ssp. *vulgaris*
Compositae	
Jerusalem artichoke	*Helianthus tuberosum* L.
Convolvulaceae	
Sweet potato	*Ipomoea batatas* (L.) Poir.
Cruciferae	
Horseradish	*Armoracia rusticana* P. Gaertn. [stn. *Nasturtium armoracia* (L.) Fries]
Radish	*Raphanus sativus* L. Radicula Group
Rutabaga	*Brassica napus* L. Neobrassica Group
Turnip	*Brassica rapa* L. Rapifera Group
Euphorbiaceae	
Cassava	*Manihot esculenta* Crantz.
Leguminosae	
Jicama	*Pachyrhizus erosus* (L.) Urban
Solanaceae	
Potato	*Solanum tuberosum* L.
Umbelliferae	
Carrot	*Daucus carota* L.
Celeriac	*Apium graveolens* L. var. *rapaceum* (Mill.) Gaud.
Parsnip	*Pastinaca sativa* L.
Monocots	
Amaryllidaceae	
Garlic	*Allium sativum* L.
Onion	*Allium cepa* L.
Shallot	*Allium cepa* L.
Araceae	
Malanga	*Xanthosoma* spp.
Taro	*Colocasia esculenta* (L.) Schott
Cyperaceae	
Waterchestnut	*Eleocharis dulcis* (Burm.) Trin. ex Hens.
Dioscoreaceae	
Yam	*Dioscorea alata* L.
Zingiberaceae	
Ginger	*Zingiber officinale* Roscoe

sweetening''). Sweetening is desirable in parsnip, but not so in potato because the sugars cause darkening of the potato tissue during chipping and frying (Talburt and Smith, 1987).

Because of their generally high solids content, one might not expect freezing injury to be a serious concern with these crops, and beets and parsnips, along with the crucifers horseradish, rutabaga, and turnip, are in fact among the most freeze-tolerant vegetables (Hardenburg et al., 1986). In contrast, potato tubers are actually among the most freeze-susceptible vegetables. This is due to the heterogeneous distribution of dry matter within the tuber; the outermost tissues of potato tubers have the lowest dry matter content, and

Table 3 Chilling Threshold Temperatures and Visual Symptoms of Chilling Injury for Some Subtropical and Tropical Storage Organ Vegetables

Vegetable	Chilling threshold (°C)	Symptoms
Cassava	5–8	Internal breakdown, increased water loss, failure to sprout, increased decay, and loss of eating quality
Ginger	12	Accelerated softening and shriveling, oozes moisture from the surface, decay
Jicama	13–15	External decay, rubbery and translucent flesh with brown discoloration, increased water loss
Malanga	7	Tissue breakdown and internal discoloration, increased water loss, increased decay, and undesirable flavor changes
Potato	4	Mahogany browning: reddish-brown areas in the flesh; adverse effects on cooking quality
Sweet potato	12	Internal brown-black discoloration, adverse effects on cooled quality, "hard core," and accelerated decay
Taro	7–10	Tissue breakdown and internal discoloration, increased water loss, increased decay, and undesirable flavor changes
Yam	13	Tissue softening, internal discoloration (grayish flecked with reddish brown), shriveling, and decay

the second lowest content is in the heart of the tuber (Burton, 1966), corresponding to the sequence in which freeze injury symptoms (discoloration, watersoaking) appear.

Sun exposure can be damaging to onion, garlic, and potato during in-field curing, causing localized surface tissue necrosis that is referred to as "sunburn" or "sunscald" (Table 5). Light exposure also can trigger chlorophyll synthesis ("greening") in onion and potato. This would be of only cosmetic import except that in potato tubers greening is associated with the synthesis of alkaloids, including the toxic glycoalkaloid solanine (Van Es and Hartmans, 1981b).

Perhaps the only generalization that can validly be applied to all members of this group of vegetables is that mechanical injuries during harvesting operations leading to the development of decays in storage is the single most important cause of postharvest losses. A number of different bacteria and fungi that are present in the soil cause postharvest diseases in underground storage organ vegetables (Table 6). In almost every case, infection occurs via inoculation of bruises, cuts, or scrapes inflicted during harvest. Adequate ventilation in storage is critical for many of these crops in order to maintain dry surfaces on the bulbs, corms, roots, and tubers, since moisture favors germination and growth of pathogenic microbes. Bacterial soft rot may also begin with the presence of the bacteria within the lenticels of wet potato tubers that have no mechanical damage at all. This occurs because the causal organisms (*Erwinia carotovora* ssp. *carotovora* and *E. carotovora* ssp. *atroseptica*) are facultative anaerobes, and also because anaerobic potato tissue becomes highly susceptible to infection (Burton and Wiggington, 1970). A layer of water on the surface of the tuber, which reduces O_2 permeation, thus favors soft rot development (Bartz and Kelman, 1986).

Wound healing is a physiological process common to many plant tissues (Lipetz, 1970; Rittinger et al., 1987), including the underground storage organs cassava, malanga, potato, sweet potato, taro, and yam (Morris et al., 1989; Rivi et al., 1996). Curing involves

Table 4 Composition of Underground Storage Organ Vegetables (Amounts per 100-g Edible Portion Raw Product)

Vegetable	Water (%)	Calories	Protein (g)	Fat (g)	Ca (mg)	K (mg)	Vitamins A (IU)	Vitamins C (mg)
Beet	87.32	44	1.48	0.14	16	324	20	11.0
Carrot	87.79	43	1.03	0.19	27	323	28,129	9.3
Cassava	68.51	120	3.10	0.39	91	764	10	48.2
Celeriac	88.00	39	1.50	0.30	43	300	0	8.0
Garlic	58.58	149	6.36	0.50	181	401	0	31.2
Ginger	81.67	69	1.74	0.73	18	415	0	5.0
Jerusalem artichoke	78.01	76	2.00	0.01	14	—	20	4.0
Jicama	89.15	41	1.40	0.20	15	175	0	20.0
Onion	90.82	34	1.18	0.26	25	155	0	8.4
Parsnip	79.53	75	1.20	0.30	36	375	0	17.0
Potato	78.96	79	2.07	0.10	7	543	—	19.7
Radish	94.84	17	0.60	0.54	21	232	8	22.8
Rutabaga	89.66	36	1.20	0.20	47	337	0	25.0
Shallot	79.80	72	2.50	0.10	37	334	—	8.0
Sweet potato	72.84	105	1.65	0.30	22	204	20,063	22.7
Taro	70.64	107	1.50	0.20	43	591	0	4.5
Turnip	91.87	27	0.90	0.10	30	191	0	21.0
Waterchestnut	73.46	106	1.40	0.10	11	584	0	4.0
Yam	69.60	118	1.53	0.17	17	816	0	17.1

Source: Haytowitz and Matthews, 1984.

Table 5 Physiological Disorders of Underground Storage Organ Vegetables

Freezing injury
Chilling injury of tropical storage organ vegetables
Heat injury (sunburn, sunscald) of onion, garlic, and potato during field curing
Greening due to exposure to light in onion and potato
Translucent scales on onions
Waxy breakdown of garlic
Pithiness of radishes (senescence related)
Internal black spot of beets (boron deficiency)
Stem-end discoloration of potato
Internal black spot of potatoes (bruising, predisposed by K deficiency)
Hollow heart of potatoes (calcium deficiency)
Blackheart of potatoes due to preharvest or postharvest low O_2, especially at high temperatures
Vascular streaking of cassava (ethylene-related disorder promoted by mechanical injury and water loss)

holding the storage organs in conditions of high temperature and high relative humidity (RH) that are conducive to wound healing (Table 7). The physiological sequence of wound healing during curing is (1) localized desiccation at the sites of wounds, (2) sealing of several layers of cells below the wounds by suberization and lignification, (3) initiation of cell division further down to form a cambial layer called the phellogen, and (4) cell division toward the outside to form perhaps four to eight layers of cork cells called the phellem (Kays, 1991). The newly formed suberized cell layer and the phellem act as a hydrophobic barrier to limit water loss during storage. Additionally, the healed wounds are resistant to infection by pathogenic microorganisms. Adequate wound healing may occur under a rather narrow set of conditions that depend on the species. For example, malanga cormels formed five to eight layers of cork cells in 7 days at 30°C or 35°C and 95% RH, but none at either 25°C or 40°C (Bikomo and Brecht, 1991). While high humidity is necessary for wound healing to occur, a saturated water atmosphere is not desirable because suberization may be inhibited and callus tissue formed instead (Kays, 1991). Onions and garlic are not cured in the sense of promoting wound healing; rather, the outer

Table 6 Common Diseases of Underground Storage Organ Vegetables

Disease	Vegetables
Bacterial soft rot	Carrot, garlic, onion, parsnip, potato
Fusarium rot	Cassava, garlic, onion, potato
Gray mold rot (*Botrytis* spp.)	Carrot, garlic, onion (''neck rot''), parsnip
Rhizopus soft rot	Carrot, cassava, sweet potato
Black mold rot (*Aspergillus niger*)	Cassava, onion
Smudge (*Colletotrichum circinans*)	Onion
Blue mold rot (*Penicillium* spp.)	Cassava, garlic, onion
Black rot (*Stemphylium radicinum*)	Carrots
Watery soft rot (*Sclerotinia sclerotiorum*)	Carrots
Charcoal rot (*Macrophomina phaseoli*)	Sweet potato
Black rot (*Ceratocytis fimbriata*)	Sweet potato

Table 7 Optimum Conditions for Curing Storage Organ Vegetables

Vegetable	Temperature (°C)	RH (%)	Duration (days)
Cassava	30–35	85–90	4–7
Malanga	30–35	90–95	7
Potato			
Early crop	15–20	90–95	4–5
Late crop	10–15	90–95	10–15
Sweet potato	29–32	80–90	4–7
Taro	34–36	95	5
Waterchestnut	30–32	95–100	3
Yam	30–35	85–95	4–7
Garlic and onion	Ambient (24–32 best)	≤75	5–10 (field drying)
	35–45	60–75	0.5–3 (forced heated air)

leaf scales are dried and the dry scales themselves become a barrier to further water loss and entry of decay organisms.

The temperate root crops (beet, carrot, parsnip, radish, rutabaga, and turnip) are generally harvested when the roots have reached a marketable size. The other crops in this group are usually harvested when the storage organ is mature and full-sized, although they may be harvested either earlier due to market conditions or when the maximum number have reached marketable size in order to facilitate a once-over harvest. Physiological maturity for cassava, garlic, onion, potato, sweet potato, taro, and yam storage organs corresponds to attainment of maximum size and also maximum starch or dry matter content. This stage usually coincides with drying of the aboveground foliage, signaling the end of the growth cycle and also the beginning of a dormant period in some of these crops. (See individual crop sections for details.) Periderm thickening in cassava, potato, sweet potato, and yam also occurs at this time; when periderm formation is complete, the skin of the potato tubers no longer "slips" easily (Wilcockson et al., 1980), and this is another commonly used maturity index. The aboveground parts of the above root and tuber crops may be cut, beaten down, or killed with chemicals (i.e., desiccants) prior to harvest to hasten the belowground maturation, making the storage organs more resistant to skinning and bruising during the harvest operation.

In developed countries, underground storage organ vegetables are mechanically harvested to a greater extent than any other vegetable type. Harvesters cut, dig, and lift the bulbs, roots, or tubers from the soil and either drop them to the ground or transfer them by means of elevators to a trailer after separating them from soil, plant material, and stones (Table 8). When deposited on the ground, they are either collected by hand immediately and transferred to storage containers or left in the field to cure or dry before being collected. In less developed countries, these crops are all hand harvested, often on an "as-needed" basis, in which case the delayed harvest essentially substitutes for storage. Whether harvest is by machine or by hand, the physical damage that can occur during the digging, lifting and collecting operations, as mentioned above, is the most important factor leading to postharvest losses of these crops.

After transport to a packinghouse or storage facility, either in bulk or in bags or cartons, the crop may be cleaned by washing in water, especially if the vegetable is usually eaten raw and the skin is going to be consumed, as for carrots and radishes; most of the other underground storage organ vegetables are cleaned by dry brushing if at all before

Table 8 Generalized Postharvest Handling Procedure for Underground Storage Organ Vegetables

Step	Function
1.	Mechanical harvest (digging, lifting) except hand harvesting of sweet potatoes
2.	Curing (in field) of potatoes, onions, garlic, and tropical crops
3.	Field storage of potatoes and tropical storage organ vegetables in pits, trenches, or clamps
4.	Collection into containers or into bulk trailers
5.	Transport to packinghouse and unloading
6.	Cleaning by dry brushing or with water
7.	Sorting to eliminate defects
8.	Sizing
9.	Packing in bags or cartons; consumer packs placed within master containers
10.	Palletization of shipping containers
11.	Cooling methods
	a. Hydrocooling of temperate storage roots and tubers
	b. Room cooling of potatoes, onions, garlic, and tropical storage organs
12.	Curing
	a. Forced-air drying (onions and garlic)
	b. High temperature and RH (potatoes and tropical storage organs)
13.	Storage
	a. Ventilated storage of potatoes, onions, garlic, and sweet potatoes in cellars and warehouses
	b. Temporary storage of temperate storage organ vegetables
	c. Long-term storage of potatoes, onions, garlic, and tropical crops following curing
14.	Fungicide treatment (sweet potato); sprout inhibitor (potato)
15.	Transport, destination handling, retail handling

storage. Brushing is much less likely to spread decay organisms than water. The problem of potential cross-contamination during water washing and the ineffectiveness of chlorination in the face of the huge amounts of soil and other organic material carried in from the field with these crops (see Chapter 23) usually means that recirculating water systems cannot be used. Sweet potatoes may receive a fungicide treatment applied as a spray or drench upon removal from storage and may also be waxed prior to marketing.

Cooling may occur before or after sorting, sizing, grading, and packing. The temperate root crops are often hydrocooled in bulk prior to the foregoing packinghouse operations, while garlic, onion, potatoes, and the tropical storage organs are room-cooled—if cooled at all—either in bulk or after packing into shipping containers. Storage of the temperate zone root crops is only temporary in order to facilitate marketing. Garlic, onion, potato, and the tropical storage organs, however, may be stored for extended periods, on the order of 3 to 6 months or more, in which case it is crucial that they first be cured (Table 7) to minimize water loss and decay-related losses during storage. Onions and potatoes are usually sprayed with maleic hydrazide a few weeks before harvest to inhibit sprouting during storage. Potatoes may also be fumigated with 3-chloroisopropyl-N-phenyl carbamate (CIPC) while in storage to further inhibit sprouting.

Curing may be accomplished in the field if the prevailing weather conditions are favorable; otherwise garlic, onions, potatoes, and the tropical underground storage organs are cured in more or less permanent structures, which may be the same as those used for storage. For garlic and onion, this requires the use of heated, forced air. In the case of potato and the tropical storage organs, curing is usually accomplished simply by restricting ventilation in order to allow the humidity and the field and respiratory heat to build up and achieve those specific conditions most conducive to wound healing of the particular crop. After curing, the temperature and humidity are reduced by ventilating the storage with outside air.

Many of these crops have traditionally been stored in the field, in pits, trenches, clamps, or piles covered with locally available insulating materials. These types of storages must either be kept small (around 5 m wide by 1.7 m deep) or be constructed with air channels to help ventilate the pile (Schouten, 1987). Various ventilated storage structures are also widely used, utilizing fans to circulate cool outside air through the pile in order to remove respiratory heat. Some of these ventilated storage structures have mechanical forced-air circulation and automated temperature and humidity control systems. Refrigerated storage is used more for the temperate underground storage organs, which require a storage temperature near 0°C for optimum quality maintenance, and less for the subtropical and tropical crops, depending of course on economic considerations, since mechanically refrigerated storage facilities are more expensive to build and maintain than nonrefrigerated stores. Details of the construction of the various types of storage systems used for underground storage organs, from the simplest to the most sophisticated, are described by Kitinoja and Kader (1994) and Schouten (1987) and the references cited therein.

II. POSTHARVEST PHYSIOLOGY AND HANDLING OF SELECTED UNDERGROUND STORAGE ORGANS

A. Beet (*Beta vulgaris* L. ssp. vulgaris), Carrot (*Daucus carota* L.), Parsnip (*Pastinaca sativa* L.), Radish (*Raphanus sativus* L. Radicula Group), Rutabaga (*Brassica napus* L. Neobrassica Group), and Turnip (*Brassica rapa* L. Rapifera Group)

The edible portion of these temperate zone vegetables includes the root and sometimes the attached leaves. These roots are harvested when they have reached a marketable size and have dense, crisp tissues; larger roots may be tough, pithy, fibrous, stringy, or woody. Smaller roots may be immature, but a narrow root diameter may also indicate plant crowding in the field, in which case the roots may also be tough or stringy (Ryall and Lipton, 1979). In addition to root size, beet maturity may also be indicated by the rosette of leaves falling away from the center of the plant.

These vegetables are almost exclusively machine harvested and the topped roots transported in bulk to a cooling and packing facility. Damage to the thin epidermal layer of the roots can occur very easily during harvest. Hydrocooling is the best and most commonly used method to reduce the field heat of these crops and is usually applied to the loose roots after washing and before packing. Rapid movement through the packingline minimizes heat gain before the crops reach the storage rooms. Ice can also be an effective cooling medium for these crops. Although these vegetables are generally not as perishable as leafy and succulent crops or immature fruit vegetables (see Chapters 25 and 28, respectively), they still need to be cooled at least on the day of harvest in order to reduce wilting and shriveling, limit heating from respiration, and prevent establishment of infection by decay organisms.

Storage at high humidity near 0°C maximizes the shelf life of these vegetables.

Radish has the shortest potential shelf life in this group, becoming pithy or spongy after only 3 to 4 weeks at 0°C, compared with about 4 to 6 months for the rest of the group (Hardenberg et al., 1986). Their susceptibility to water loss is the greatest among the underground storage organ vegetables (Burton, 1982). Shrivel symptoms have been reported to occur with 8% weight loss in carrots, 7% in topped beets, parsnips, and turnips, and 5% for bunched beets and turnips (Robinson et al., 1975). Within any one of these crops, the smaller roots will be more susceptible to water loss because of their larger surface-to-volume ratio. (See Chapter 5.) Because of this propensity to lose water, these vegetables are very commonly packed in perforated or semipermeable plastic bags of various sizes and configurations. In the absence of such packaging, the storage RH should be maintained at the highest possible level that does not result in condensation. A large amount of research has demonstrated that the surface tissues of these roots retain their integrity best under very high RH (Ryall and Lipton, 1979; Stoll and Weichmann, 1987) and that this does not lead to higher decay, as had been assumed previously. Rutabaga and turnip are often waxed before marketing to further protect against water loss and shriveling. Maintaining these vegetables at near 0°C limits textural and compositional changes and will completely inhibit the growth of decay organisms and the regrowth of tops. Storage at 0°C would also be expected to minimize the effects of ethylene exposure during storage, including the synthesis of bitter tasting phenolic compounds in carrot and parsnip roots (Carlton et al., 1961; Sarkar and Phan, 1974; Shattuck et al., 1988).

Beets, carrots, and radishes may be handled with or without their aboveground foliage (''bunched'' or ''topped,'' respectively), although bunched are nowadays less common. The shelf life of bunched roots is limited by the deterioration of the tops and is thus much shorter than topped roots; for example, 10 to 14 days versus 4 to 6 months at 0°C for bunched versus topped beets, respectively (Hardenburg, et al., 1986). Besides their inherently greater perishability, the leaf tissues also lose water much faster than the roots and draw additional water from the roots so that the root tissue of bunched roots loses water faster than when they are handled as topped roots.

B. Onion (*Allium cepa* L.) and Garlic (*Allium sativum* L.)

The Allium crops, onion and garlic, are widely grown around the world for fresh consumption and for processing. The climate, culture, and economies in these countries, and the uses of these crops are extremely variable, and thus, so too are the methods for their production and handling. The storability of onions and garlic is very much influenced by the environment during growth, cultivation practices, and cultivar types (Fenwick and Hanley, 1985). Onion and garlic are cool-season crops that form bulbs in response to longer days and shorter nights and warmer temperatures in the spring. ''Short-day'' onion cultivars are those that form bulbs relatively early in the spring; the term is not related to flowering as usually employed. The onion bulb consists of a very short stem and leaves, the latter bases of which are more or less swollen. The outermost leaves are less swollen at the base and the senescent, outermost leaves form the dry ''skin'' of the bulb. A garlic bulb, in contrast, is composed of several cloves that initiate in the axils of the inner leaves and are enclosed within several layers of sheath leaves.

It is important to harvest onions and garlic at the proper maturity for storage because storage losses are much higher for bulbs harvested too early or too late than for those harvested when the necks soften and the tops just begin to fall over (Bottcher, 1999; Smittle and Maw, 1988). Harvested onions and garlic must be cured before storage by placing them in conditions that promote drying of the neck and outer bulb scales. At a weight loss of about 5%, the tight neck and dry scales form an effective barrier to further water loss as well as to attack by microorganisms. In growing areas in which the prevailing weather conditions allow it, the bulbs are cured in windrows in the field or in open sheds (Tables 7 and 8); otherwise, forced heated air is used to rapidly dry the neck and outer scales (Maw et al., 1997). Field-cured onion and garlic bulbs must be protected from the sun to prevent sunscald and are usually covered with cloth bags or arranged in the field in such a way that the tops of one row cover the bulbs of the next.

Mature onions and garlic bulbs are in a state of rest after they are harvested. The length of the rest period and subsequent dormancy varies among cultivars, which consequently have different storage potentials. Breaking of dormancy is inhibited at temperatures near 0°C or 30°C. Dormancy can be released and the bulbs begin to sprout most rapidly at intermediate temperatures of 10–15°C (Abdalla and Mann, 1963; Mann and Lewis, 1956). Properly cured garlic and Globe and Spanish onion bulbs may be stored for 6 months or more at 0°C, but only about 1 month at 30°C (Hardenburg et al., 1986) because, although dormancy is maintained at the higher temperature, weight loss and decay are accelerated. Mild, sweet Bermuda or short-day-type onions are not well suited for extended storage, but due to their desirability they may be stored in a controlled atmosphere (CA) of 3% O_2 plus 5% CO_2 at 1°C to extend the marketing season (Smittle, 1988). Maintaining low humidity (no more than 65–70% RH) is critical for successful storage in air or CA because high humidity favors both decay and root growth.

Onions and garlic are subject to much the same diseases and disorders. High temperatures during growth or after harvest may also lead to similar disorders, called "translucent scale" in onion and "waxy breakdown" in garlic (Table 5). Both disorders appear to be related to accelerated senescence (Ryall and Lipton, 1979). Both onion and garlic bulbs may be damaged by solar exposure ("sunburn"), which leads to accelerated water loss from the affected outer scales and is often followed by bacterial rot. Less intense light exposure can cause greening of the outer scales of onion bulbs. The most serious diseases of onion and garlic are fungal in nature (Table 6). Botrytis gray mold ("neck rot") is probably the most serious onion storage disease worldwide and occurs most commonly in onions that either have been incompletely cured or were not cured promptly after harvest, especially if the bulbs were also not cooled rapidly (within 2 to 3 days) to a 0°C storage temperature (Ryall and Lipton, 1979). Infection occurs via the cut ends of the onion leaves. Blue mold rot, caused by Penicillium spp., is the most common fungal storage disease of garlic. Low temperature, as well as low humidity, which helps to maintain the outer scales in a dry condition, are the most important storage factors for reducing rots.

C. Waterchestnut [*Eleocharis dulcis* (Burm.) Trin. ex Hens.]

The waterchestnut or matai is primarily cultivated throughout tropical Asia for its edible corms. The plant is a hydrophyte and is grown under flooded conditions similar to paddy rice. There are two types, the sweet 'hon matai' and starchy 'sui matai.' High-quality hon matai waterchestnuts are tender, crisp, and somewhat sweet with white interior tissue. The corms may be eaten raw, but maintain their crispness when cooked and are usually consumed in that way.

Corms of waterchestnuts mature after the plant tops have died or have been killed by frost in the fall. Mature corms can be recognized by their well-developed, lignified, dark, shell-like epidermis. The corms keep well underground and harvest can be delayed for up to 4 months after top die-down (Hodge, 1956). It has been reported that sugar content more than doubled (2.3% v. 5.3% F.W.) in corms harvested in December in the southeastern United States compared to October-harvested corms (Twigg et al., 1957). Waterchestnut corms, however, also became less tender and more fibrous when harvest was delayed from October to December or February (Brecht et al., 1992). Corms over 30 mm in diameter with no physical injury from harvesting are considered to be marketable (De Rigo and Winters, 1964), and corms over 40 mm in diameter are desirable (McGregor, 1989). Damaged areas on corms turn brown, which detracts from their appearance, and must be trimmed when the corms are peeled.

The corms are usually packed and stored at 0–2°C in film bags with moist sphagnum moss. Storage for 2 months is possible under these conditions (Ryall and Lipton, 1979). Waterchestnut corms are susceptible to water loss, which causes loss of crispness and tenderness, but texture changes are minimal in refrigerated storage if water loss is minimized (Brecht et al., 1992; Kays and Sanchez, 1984). Chilling injury is only a concern with immature corms. Symptoms of CI in waterchestnut are watersoaking, internal brown discoloration, and external decay. Immature waterchestnut corms were injured within 10 days at 1°C; by 21 days they were shriveled and badly discolored (Brecht et al., 1992). Waterchestnut corms sweeten in low temperature storage, much like potato tubers and parsnip roots (DeRigo and Winters, 1964). Starch to sugar conversion can result in doubling or tripling of sugar levels within 1 month of storage with no further increase over longer storage times; maximum sugar levels are reached at 10°C and in early-harvested, larger corms (Brecht et al., 1992), but 10°C storage is limited to 1 month because of decay.

Decay, mainly due to *Fusarium* and *Geotrichum* spp., was a problem at storage temperatures greater than 5°C and in immature corms with CI (Brecht et al., 1992). Black rot (*Cerastomella paradoxa*) and Trichoderma rot (*Trichoderma viride*) have also been reported, with Black rot being susceptible to control by curing the corms at 30–32°C and 100% RH for 3 days. (See Ryall and Lipton, 1979.)

D. Potato (*Solanum tuberosum* L.)

Potatoes are widely grown and consumed in countries throughout the temperate zone, as well as in tropical highlands in which moderate temperatures prevail. The potato crop can be separated into two categories: mature or late-crop potatoes that are harvested after the tubers have reached physiological maturity, and immature, early-crop, or "new" potatoes, which are harvested when the tubers are still increasing in size. Besides attainment of full size, tuber physiological maturity is indicated by the soluble sugar content reaching a minimum and the starch content a maximum, and full development of a thickened periderm layer ("skin") below the epidermis (van Es and Hartmans, 1981b). Early-crop potatoes are harvested to meet the demand for fresh market, although a few are also used for chipping. Most of the late-crop potatoes are used for processing or placed into storage for extended marketing.

Early-crop potatoes are much more perishable than late-crop potatoes, with a much shorter potential storage life, but they are usually marketed without any storage to take advantage of high prices. The respiration rate of immature tubers at harvest is about four to five times greater than for mature tubers, but can decline to the mature, at-harvest value in about 1 month at 10°C (Burton, 1964). The phellogen of early-crop potato tubers is still actively dividing at the time of harvest and the skin is thus easily sloughed off. Early-crop potatoes are also more succulent and easily bruised than late-crop tubers. Increased mechanical damage inevitably leads to increased storage rots.

To counteract the negative effects of lack of maturity, both early-crop and late-crop potato vines are almost always treated with a dessicant and/or mechanically beaten or cut at least 10 to 20 days before the desired harvest date. This simulates the natural seasonal decline of the plants that occurs in the traditional fall-harvested crop and promotes tuber maturation in terms of skin set and reduced bruising. Too rapid killing may cause discoloration of the vascular ring at the stem end of tubers (''stem-end discoloration'' = SED), especially in hot weather and dry soil (Halderson et al., 1985), which can be a serious defect for processing potatoes.

Potato harvest should be managed to be as gentle as possible, with minimal drops and the harvesters adjusted to maintain full chains, which minimizes bruising. Harvesting in cold, wet weather should be avoided because potato tubers bruise more easily at lower temperatures (Mathew and Hyde, 1997), and wet conditions would facilitate infection of any harvest wounds that occur. Two types of bruising can occur, which may represent a continuum of damage type (Mathew and Hyde, 1997). ''Blackspot'' consists of small, dark, discolored areas beneath the skin that usually are not visible unless the tubers are peeled. Injured tissue changes from pink to red, and then darkens to brown and black. Blackspot can occur as a result of either impacts (during harvest or grading) or pressure (in storage). ''Shatter'' occurs as small splits in the skin that become more obvious as the injured tissue dries out. The margins of shatter bruises show the same discoloration as blackspot, but the injuries are visible on the tuber surface and penetrate deeper into the tissue. Potatoes should not be left exposed in the field after digging, in bulk trucks during loading and transport, or while waiting to be unloaded at the packinghouse. This reduces the risk of sunscald, which can lead to unsightly discolored, sunken areas that are particularly prone to invasion by soft rot bacteria (Ryall and Lipton, 1979).

Potato storage provides a uniform flow of product to fresh market and processing plants throughout the year. When mature potatoes are placed in storage, they are in a state of rest (i.e., they will not sprout even if exposed to conducive conditions). Sprouting may begin after 2 to 3 months of storage, and dormancy is maintained beyond this point by low storage temperature and prior application of sprout-inhibiting chemicals (van Es and Hartmans, 1981a). Low temperature sweetening, which involves conversion of storage starch to soluble sugars, can be a serious problem in potatoes intended for processing. Early-crop potatoes, which are not usually processed, are more sensitive to low temperature than late-crop tubers (Hardenburg et al., 1986; Isherwood, 1976). The starch-to-sugar conversion at low temperature can be reversed by reconditioning the tubers at a higher temperature (19–21°C) for 1 to 4 weeks, but the original sugar level is never fully attained (Burton, 1975), and even fully mature, fall-crop potatoes may never recondition satisfactorily for processing if they were previously stored at 4°C (Ryall and Lipton, 1979).

If storage will extend for more than a few weeks, potatoes should first be cured (Table 7). Early-crop potatoes can be stored for 4 to 5 months at 4°C if they have been cured, but there is usually no reason to store new potatoes. Most of the late-crop potatoes are stored, and most of this storage is in common, air-ventilated storage (i.e., not refrigerated). For maximum storage life, however, and depending on the intended use of the potatoes, initial curing followed by refrigerated storage at certain optimum storage temperatures is desirable. A storage temperature of 4°C is optimum for table stock, for which low temperature sweetening is not a major concern, and cured ''Russet Burbank'' potatoes treated with a sprout inhibitor can be stored for 10 months or more at this temperature.

Potatoes for processing into frozen french fries that are stored at 6–7°C can be fried without reconditioning; they can be stored for longer times at 4°C, but then require reconditioning. Because of the need for very low reducing sugar levels, chipping potatoes are usually stored at 10–13°C, depending on the variety. Early-crop potatoes used for chipping need to be held at no less than 21°C for maintenance of chipping quality (Ryall and Lipton, 1979).

Blackheart is a physiological disorder of potato that is caused by restricted access to O_2 in the innermost tuber tissues (Davis, 1926). It sometimes occurs in tubers dug from waterlogged fields, especially in warm weather, but is more commonly a storage disorder. High respiration rates in the center of large piles of tubers in storage rooms, railcars, and truck trialers lead to heat accumulation and O_2 depletion. Blackheart can be eliminated by cooling potatoes and by designing stores and trailers with adequate ventilation to facilitate good air circulation and temperature management. Hollow heart is a physiological disorder that is sometimes confused with blackheart because it begins as a brownish, discolored area in the center of potato tubers (''brown center,'' ''brown spot''), but in more advanced cases leads to the formation of irregular, open, discolored cavities. Hollow heart is generally related to environmental stress, nutrient imbalances, and rapid or irregular tuber growth (Rex and Mazza, 1989). More recently, it has been suggested that the localized tissue necrosis that initiates hollow heart is likely to be caused by localized deficiency of calcium in the tuber pith tissue (Kleinhenz et al., 1999).

E. Sweet Potato [*Ipomoea batatas* (L.) Poir.]

There are two major types of sweet potatoes grown. ''Dry-flesh'' types (called ''boniato'' in Cuba and Florida), which are grown more in the tropics, typically have white or yellow flesh and have a dry, mealy texture after cooking. ''Moist-flesh'' sweet potatoes, which are more common in temperate areas, such as the southeastern United States, typically have orange flesh that is soft and moist after cooking. There are no definite maturity indices used for harvesting sweet potatoes (i.e., the roots may be harvested at almost any time), although roots are considered to be mature when the leaves turn yellow or the exudate from cut roots remains white rather than turning black (Yamaguchi, 1983). Sweet potato maturity coincides with high starch content and maximum concentration of carotene and total carotenoid pigments (Kotecha and Kadam, 1998). Sweet potatoes are usually harvested when the roots have reached a marketable size or to achieve maximum yield in a once-over harvest. Sweet potatoes can be grown throughout the year in tropical regions.

Sweet potatoes are harvested by cutting the vines and digging the roots, usually with a mechanical harvester. Some mechanical diggers can dig the roots, sort them, and load them onto trailers. Less sophisticated machines lift the roots and deposit them on the soil surface for manual collection. Irrigation is typically stopped 2 to 3 weeks before harvest so that the vines begin drying before they are removed and the roots harvested. Low soil moisture makes digging the roots easier and also reduces the chances of decay-causing organisms infecting the roots via harvest-inflicted wounds. The roots are easily cut, skinned, and bruised during harvest. In addition, since all roots must be cut or snapped from the plant, they all have open, broken ends that serve as sites for water loss, infection, and decay. The dug roots should not be left exposed on top of the soil for more than about 1 h to avoid sunscald. Roots should ideally be harvested during the coolest part of the day and shaded until arrival at the packinghouse or storage facility. Excessive handling is avoided by collecting sweet potato roots directly into storage crates or bins and placing them directly into the storage facility for curing.

Sweet potatoes are extremely susceptible to storage rots, which are primarily caused by fungi that infect the roots through wounds inflicted during harvest (Clark and Moyer, 1988). The most important of these is Rhizopus soft rot, which develops rapidly but requires both a wound for entry and dead host tissue (Clark and Moyer, 1988). This means that curing is essentially a race between the wound healing process in the root and the infection process by the fungus. The wound cork cells begin to form in about 2 days under optimal curing conditions. A delay of 1 or 2 days in the start of curing thus can greatly increase the incidence of storage rots. Curing is usually accomplished by placing the freshly harvested roots into storage rooms that are closed and then held for about 1 week with only enough air exchange to maintain the optimum curing temperature of 29–32°C at which wound healing is most rapid. Minimal ventilation also causes the RH to increase to the desired 80–90% necessary to promote wound healing. Periderm formation in sweet potato roots can occur within the temperature range of 15–37°C, but the process is slow below 25°C (Ravi et al., 1996). As much as 4% weight loss by sweet potatoes may occur under optimal curing conditions (Kushman, 1975), but subsequent weight loss during storage is much reduced compared with uncured roots. Higher weight loss during curing indicated slower wound healing and was positively correlated with increased decay development during storage. Like potato, sweet potato periderm formation is inhibited by reduced O_2 levels ($\leq$8%) and elevated CO_2 levels ($\geq$10%) (Delate and Brecht, 1989), so sufficient air circulation within the mass of sweet potatoes to avoid localized atmosphere modification is important.

After curing, the storage room temperature is lowered to 13–16°C, and at this temperature sweet potatoes can be held for 6 or 7 months in excellent condition (Kushman and Wright, 1969). In tropical areas, sweet potatoes can be harvested all year, and little attempt is made to store the harvested roots. Curing procedures are not widely known in the tropics, therefore tropical sweet potatoes do not usually last for more than 2 to 4 weeks in storage (O'Hair, 1990). Unlike potatoes and onions, there is no strong period of rest in sweet potatoes, which can sprout very quickly after harvest under conducive temperature and humidity conditions (Kushman and Wright, 1969). Temperature control during storage is critical because CI can develop rapidly at temperatures of 10°C or lower and the growth of decay-causing organisms such as *Rhizopus* and *Fusarium* increases rapidly above 16°C (Cooley et al., 1954). At temperatures above 16°C, respiration rate, dry matter loss, internal breakdown (pithiness), and sprouting also increase (Edmond and Ammerman, 1971). Chilling injury of sweet potato increases with decreasing temperature, and increasing exposure time and uncured roots are more susceptible to CI than cured roots (Ravi and Aked, 1996). Injury to freshly harvested, uncured roots occurred after 2 days at 0°C, 4 days at 4°C, and 10 days at 10°C, while cured sweet potatoes were not damaged for 30 days at 10°C (Lutz, 1945). Uncured sweet potatoes suffered 100% losses due to decay after 4.5 months at 10°C. Hardcore is the most sensitive indicator of CI, occurring after as little as 0.5 day exposure to 1°C in some sweet potato cultivars (Daines et al., 1976).

F. Cassava (*Manihot esculenta* L.)

The underground storage organ of cassava (manioc, yucca, mandioca, tapioca) is a starchy storage root that differs from potato tubers and the other tropical underground storage organ vegetables in that it has no perennating function; that is, it cannot be used for vegetative propagation since it has no bud primordia, nor does it exhibit a period of rest or dormancy after harvest. Cassava is propagated by stem cuttings from which adventitious roots arise at the base and from the buds below the soil. Usually from three to 10 roots per plant become storage roots. The storage roots can be harvested from 6 to 24 months after planting, when the culinary characteristics are optimal, depending on the cultivar and the growing conditions (El-Sharkaway, 1993). Cassava has an extremely wide harvest window, which makes it a very flexible food source for subsistence farmers. For example, roots of early cassava types may reach marketable size by 6 months after planting, given favorable climatic conditions, but harvest may be delayed until 9 to 12 months to obtain highest yields or as ''in-ground'' storage. Although the roots are usually harvested on an ''as-needed'' basis, if they are left too long in the ground and regrowth occurs, they lose starch and become fibrous and inedible (O'Hair, 1989). Other disadvantages of in-ground storage include the inefficiency of keeping arable land unavailable for further cropping and increased susceptibility to pathogenic loss the longer the roots remain in the ground (O'Hair, 1990; Ravi et al., 1996). Pruning the aboveground parts of the plant to leave a 20–30-cm stub 2 to 3 weeks before harvest is a common practice that is reported to harden the roots and delay postharvest physiological deterioration (Ravi and Aked, 1996).

Cassava has long been considered to have an unavoidably short potential postharvest storage life on the order of only 1 to 2 days under ambient conditions due to rapid physiological deterioration (''vascular streaking''; Table 5) followed closely by microbial spoilage (Booth and Coursey, 1974). Cassava roots are chilling sensitive, exhibit internal breakdown, increased water loss, increased decay, loss of eating quality, and failure to sprout following storage at temperatures below 5–8°C, depending on cultivar and growing conditions (Table 3). The rapid development of vascular streaking at nonchilling temperatures, however, has precluded storage at higher temperatures and led to recommendations that cassava is best stored at 0–5°C (Ingram and Humphries, 1972) followed by immediate consumption when removed from storage (before CI symptoms have a chance to develop upon warming). At such low temperatures, the reactions leading to vascular streaking and the growth of decay organisms are inhibited, and cassava roots harvested in good condition can be expected to store for as long as 6 months. In areas in which refrigeration is not generally available, which encompasses the vast majority of worldwide cassava production, it is common practice to rebury the roots (Ravi et al., 1996). Cassava roots can be kept in good condition for several months in this manner. In general, all attempts to devise aboveground structures for storage of cassava roots under ambient conditions have been unsuccessful.

Physiological deterioration or vascular streaking of cassava roots has been extensively studied for 50 years and will be only briefly discussed here. Ravi and Aked (1996) have reviewed the development of our understanding of this physiological disorder. Vascular streaking is characterized by the appearance, within 24 to 48 h after harvest, of initially blue, later black, radial streaks caused by darkening of the xylem vessels. The discoloration spreads to the nonvascular tissue and eventually takes on a diffuse brown appearance. The location, extent, and severity of vascular streaking are all closely associated with mechanical damage to the roots. Vascular streaking is followed by microbial invasion, which advances the deterioration already initiated, but has been ruled out as a causative factor in the disorder. The discoloration has been shown to be caused by the biosynthesis and then oxidation (by polyphenol oxidase; PPO) of the coumarin derivative scopoletin. Activity of phenylalanine ammonia lyase (PAL), which catalyzes the first committed step in phenolic biosynthesis, has been shown to occur in parallel with vascular streaking development. Variation among cassava cultivars in propensity to develop vascular streaking has been associated with varying levels of scopoletin, and also differences in rates of wound respiration and wound ethylene production.

Vascular streaking is inhibited by a number of environmental factors, including low temperature (0–5°C), saturated humidity or barriers to water loss such as films and waxes, hot water treatment (53°C for 45 min), reduced O_2, and elevated CO_2. Oxygen is required for PPO activity and for ethylene biosynthesis, and CO_2 is a PPO inhibitor and a competitive inhibitor of ethylene action; ethylene triggers de novo synthesis of PAL in many plant tissues (see Chapter 10.) Vascular streaking is also reduced by curing (Table 7) and by preharvest pruning of the aboveground plant parts. Attack by microbial pathogens responsible for root rots in cassava also stimulates vascular streaking development. It has been suggested that vascular streaking is caused by local stress produced by harvest-inflicted wounding and by the high rates of water loss at sites of mechanical damage (Marriott et al., 1978). Aracena et al. (1992) tested this hypothesis by holding uniformly wounded roots in a factorial arrangement of high (95–98%) or low (54–56%) RH, and air (21% O_2) or reduced (1%) O_2 at 25°C. Reduced O_2 inhibited vascular streaking that occurred at low RH in normal atmosphere, but had no effect on the roots when RH was high, in which case vascular streaking was essentially absent. Aracena (1993) also found that exposure of wounded cassava roots to ethylene (75 ppm) increased vascular streaking even if the humidity around the roots was maintained at 95–98% RH. This clearly demonstrates that this physiological disorder of cassava is a stress-induced ethylene response that begins with the mechanical damage suffered by the roots at harvest and during handling and is exacerbated by localized water stress in the damaged tissues. Currently, cassava produced for export is coated with paraffin wax, which creates an internal modified atmosphere of reduced O_2 and elevated CO_2 and blocks water loss, effectively inhibiting vascular streaking during transport and handling at 5°C plus ambient retail handling.

G. Jicama [*Pachyrhizus erosus* (L.) Urban]

Jicama or yam bean is a turnip-shaped root native to Mexico and Central America that has recently increased in popularity outside its native region. Jicama roots are harvested at various stages of development, as there is no obvious indicator of maturity (Fernandez et al., 1997). The flesh of jicama roots has a crunchy texture and mild, sweet flavor and is usually eaten raw. Storage of jicama root is limited primarily by moisture loss and CI. In commercial practice jicama is stored briefly in ventilated ambient air storage to regulate market supplies. There is a continuous decrease of starch and reducing sugar content and a corresponding increase in sucrose during storage (Bergsma and Brecht, 1992; Paull and Chen, 1988). The threshold temperature for CI has been variously reported to lie between 10–15°C (Bergsma and Brecht, 1992; Cantwell et al., 1992; Mercado-Silva and Cantwell, 1998; Mercado-Silva et al., 1998a; 1998b). Symptoms of CI in jicama are primarily increased weight loss, decay, flesh translucency or discoloration, and loss of crisp texture, becoming ''rubbery'' with severe chilling. Internal discoloration typically occurs from the skin inward and is more common and more severe in moderately chilled roots (stored at 10°C) than those stored at lower temperatures, in which the pulp takes on a translucent appearance but does not necessarily develop brown discoloration (Mercado-Silva and Cantwell, 1998). Although moderate storage temperatures are necessary to avoid CI, moisture loss from jicama roots can be severe at 15°C and higher temperatures without waxing or the use of plastic film wraps (Bergsma and Brecht, 1992). Bergsma and Brecht (1992) found no evidence of periderm formation in jicama roots after 8 days at 25 or 30°C and 100% RH compared with roots examined at harvest or after storage at 20°C and ambient RH. Besides chilling-related decay, most of the decays found in commercial shipments of jicama are related to mechanical damage (Bruton, 1983).

H. Malanga (*Xanthosoma* spp.) and Taro [*Colocasia esculenta* (L.) Schott.]

Taro (dasheen, eddoe, old cocoyam, tannier) is grown primarily in the Pacific Islands, but is also grown to some extent in the Caribbean, as well as tropical Asia and Africa. The related aroid malanga (new cocoyam, tannia, yautia) is grown primarily in the Caribbean and to some extent in tropical Africa. The main cultivated specie of malanga is *X. sagittifolium*, although many other species are also grown (O'Hair and Asokan, 1986). The edible portion of these vegetables is the corm formed from the stem and the cormels that form from lateral buds. *Colocasia esculenta* var. *esculenta* (taro, dasheen) forms one large edible corm and a few (4 to 10) cormels; *Colocasia esculenta* var. *antiquorum* (eddoe, old cocoyam) forms an often inedible small-to-medium-size corm and many (15 to 40) small, edible cormels (Cooke et al., 1988).

About 6 to 10 months is required for taro corms to reach a size large enough to harvest. Like sweet potatoes, the edible aroids can be grown throughout the year, which minimizes the need for storage. Maturity for taro (*C. esculenta* var. *esculenta*) occurs when the corm stops growing, cormels begin to form, and the leaf canopy decreases to two or three leaves. This usually occurs after about 8 to 12 months. As the cormels in turn mature into main plants, the corm becomes fibrous, tough, and eventually inedible. The same sequence of events occurs with malanga and *C. esculenta* var. *antiquorum*, except the cormels are the desired edible part of the plant. Cormels may be harvested by removing soil to expose and remove the largest cormels, leaving the smaller cormels to continue enlarging. Since harvest involves separating the corms or cormels from the plant by cutting, there is at least one unavoidable wound on each. Good quality taro and malanga corms and cormels have a dry, mealy texture when cooked and they are prepared in various ways like potato.

As mentioned above, taro and malanga are not often stored for any appreciable length of time; rather, they are harvested as needed, making use of "in-ground" storage. When held under ventilated, ambient conditions, the harvested corms typically succumb to decay within 1 or 2 weeks as wound pathogens develop. Adequate ventilation is required to maintain a dry corm surface to reduce decay, but unfortunately increases water loss. Dipping malanga and taro in 1% NaOCl is a reasonably effective means of reducing storage rots (Bikomo and Brecht, 1991; Rickard, 1983). The very high concentration is necessary because of the rough, fibrous surfaces of the corms or cormels, which apparently inactivate much of the chlorine. (See Chapter 23.) In the absence of decay, ambient storage for 4 to 6 weeks is possible before sprouting begins (O'Hair and Asokan, 1986; Ravi et al., 1996), and Agbor-Egbe and Rickard (1991) reported that both malanga and taro were stored successfully for 5 to 6 weeks at 15°C and 85% RH. Storage of aroids in leaf-lined pits or in perforated plastic bags have produced similar results, but with minimal weight loss (Bikoma and Brecht, 1991; Ravi et al., 1996), probably due to reduction of water loss and promotion of wound healing. Wound periderm formation in both malanga and taro is optimal at about 30–35°C and 95% RH (Been et al., 1975; Bikomo and Brecht, 1991; Passam, 1982; Rickard, 1983).

Both malanga and taro are chilling sensitive (Table 3), with a chilling threshold somewhere around 7–10°C. The most commonly recommended storage conditions for malanga cormels are 7°C and 85% RH (Onwueme, 1978; Purseglove, 1972; Tindall, 1983). Similarly, it has been reported that taro corms can be stored at 7°C for 3.5 months (Hashad et al., 1956). Nevertheless, there seems to have been little in the way of systematic evaluation of different storage temperatures for either malanga or taro. Chilling injury symptoms (internal browning) in taro corms were observed after 10 days at 4°C (Rhee and Iwata, 1982). We have observed that CI symptom development in malanga corms occurred at 0 and 5°C, but not at 10°C during 3 weeks storage (Brecht and Sherman, unpublished).

I. Yam (*Dioscorea* spp.)

The genus *Dioscorea* contains about ten species that are grown for their edible tubers, with the most important of those being *D. alata* (Southeast Asia), *D. esculenta* (Southeast Asia), and *D. rotundata* (Africa) (O'Hair, 1990). *D. alata* and *D. rotundata* produce a single tuber per plant, while *D. esculenta* produces 4 to 20 tubers. Yam tubers are ready to harvest when the leaves turn yellow and the vine dries, at which point all plant growth has ceased and the mature tubers are dormant. The harvest season usually follows the end of the rainy season. Harvest is exclusively by hand digging, and care must be taken to minimize the occurrence of injuries, which provide entry for decay. Yam tubers are susceptible after harvest to attack by a number of fungi, including *Botryodiplodia* spp., *Penicillium* spp., *Aspergillus* spp., and *Fusarium* spp. (Masalkar and Keskar, 1998). Sometimes an early harvest is made by removing the lower portion of the tuber, leaving the "head" to heal and continue growth for a second harvest (Yamaguchi, 1983).

Yam tubers can be stored under ambient conditions as long as they remain decay-free and physiologically dormant. Storage is thus limited either by decay or sprouting (Passam and Noon, 1977). Once dormancy ends and sprouting begins, the tubers senesce rapidly. The ambient storage life varies among different yam species and varieties, but is on the order of 3 to 4 months in the absence of decay (Coursey, 1967). *D. rotundata* has a relatively long dormant period and is considered to be the best storing of the yams (O'Hair, 1990). Ambient storage may consist of piling the yams in heaps in some protected spot or storing them in shaded sheds, huts, or barns constructed for the purpose (Kitinoja and Kader, 1994). Adequate ventilation is very important in minimizing decay losses. The yam barns of West Africa are unique among vegetable storage structures in that the tubers are tied to the framework of the structure. Often, the vertical poles are "live poles" that take root and sprout to provide shade for the barn.

Curing yam tubers heals harvest wounds, thereby reducing water loss and decay (Been et al., 1977; Gonzalez and Collazo deRivera, 1972). The optimum conditions for curing yam tubers (Table 7) have proven to be similar for all of the yam types investigated (Ravi et al., 1996) and are quite close to the typical ambient, tropical conditions at the time of year in which yams are harvested. Yams are extremely chilling sensitive (Table 3) and should not be held below 16°C for long-term storage (Hardenburg et al., 1986). Chilling injury has been reported to occur within 5 weeks at 7°C, 3 weeks at 3°C, and 5 days at 2°C (Coursey, 1968; Gonzalez and Collazo deRivera, 1972). Wound healing in yams can be strongly delayed at temperatures below 35°C and apparently does not occur at all at the optimum storage temperature (Passam et al., 1976); therefore, it is necessary to cure yams prior to refrigerated storage or water loss and decay may be severe. Cured yams stored at 16°C have a potential storage life that is about double that of uncured yams in ventilated ambient storage (6 to 7 months versus 3 to 4 months, respectively).

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