ANNUAL REVIEWS

Annual Review of Phytopathology

Phytosanitary Challenges and Solutions for Roots and Tubers in the Tropics

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Annu. Rev. Phytopathol. 2025. 63:627–50

The *Annual Review of Phytopathology* is online at phyto.annualreviews.org

https://doi.org/10.1146/annurev-phyto-021722-030316

Keywords

vegetatively propagated crops, diseases, control methods, planting material, seed, seed systems

Abstract

Vegetatively propagated crops such as cassava, potato, sweetpotato, and yam, or roots and tubers (RTs), play a major role in food security in low- and middle-income countries, yet phytosanitary issues in the tropics lead to substantial yield and quality losses. Challenges to production include institutional limitations that prevent effective responses and potential buildup of pathogens during clonal propagation. Addressing these challenges in a climate change context and diverse sociocultural environments requires a multifaceted approach, including improving access and availability to clean seed by strengthening seed systems; breeding for host resistance and disseminating resistant varieties; strengthening on-farm seed management; and designing effective policies and regulations to deal with seedborne diseases. Vital cross-cutting activities that can help to tackle the phytosanitary challenges of RTs include capacity strengthening, research on emergent pathogens, and improving regional cooperation and harmonization of phytosanitary standards to manage transboundary seed movement.

1. INTRODUCTION

Major vegetatively propagated crops that support food security in the tropics include cassava (*Manihot esculenta*), potato (*Solanum tuberosum*), sweetpotato (*Ipomoea batatas*), and yam [*Dioscorea rotundata-cayenensis* (white yam), and *Dioscorea alata* (water yam)]. Collectively referred to as roots and tubers (RTs), they play a major role in food security in low- and middle-income countries (LMICs), especially in smallholder production systems (146) (**Figure 1**). Many RTs can be grown with few inputs, often under harsh conditions, and sustain families in regions affected by disaster or crop failure (89). Their resilient traits include (*a*) high energy and nutrient output per growing period and unit area, combined with high drought-stress tolerance (e.g., in sweetpotato; 62); (*b*) the capacity to survive under dry conditions by using water from deep soil layers, using controlled stomatal closure, and shedding leaves during dry periods (e.g., in cassava; 9); and (*c*) the ability to thrive under high temperatures and survive with limited inputs for extended periods (89). As important cash crops, they can help boost family incomes and are frequently grown or marketed by women (147). Moreover, they can provide important nutritional benefits. For example, orange-fleshed sweetpotato (OFSP) is high in provitamin A (beta-carotene), and just 125 g of cooked OFSP root can meet the daily vitamin A needs of a young child (84).

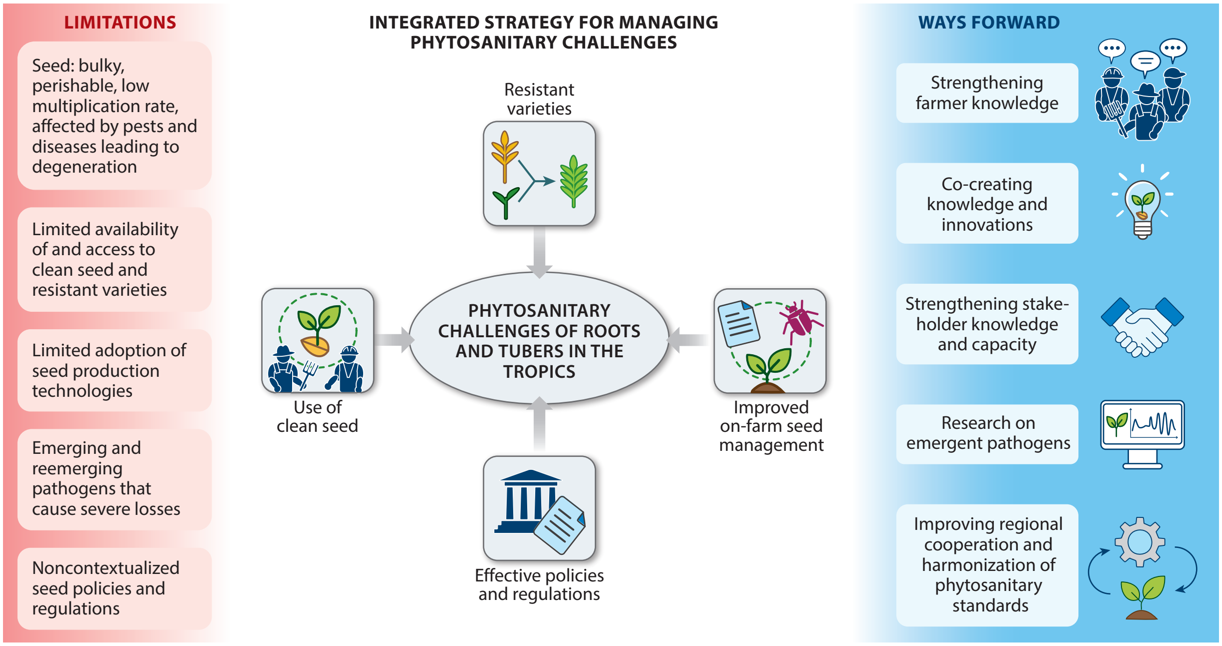

Figure 1

Schematic representation of phytosanitary challenges and solutions for roots and tubers in the tropics.

Vegetative, or clonal, propagation is a key characteristic of RTs. Planting material or seed (stems, tubers, vines, roots, plantlets) is bulky and perishable, has a low multiplication rate, and, most importantly, is affected by many pests and diseases that build up in successive cycles of clonal propagation, leading to yield and quality decline, i.e., seed degeneration (14). In poor rural households in LMICs, planting material is usually obtained from several sources (137), such as previous harvests, family and friends, or local traders, with no formal certification. Therefore, pathogens causing seed degeneration can spread through seed, causing significant yield and quality losses (57, 63, 75, 132, 148). In high-income countries, seed degeneration in crops such as potato has largely been overcome by implementing formal seed certification programs, especially for large-scale production (48). However, formal seed certification has not been as successful as expected in systems for low-income farmers who grow RTs in the tropics (for potato, see 148). This is generally because of the lack of infrastructure (e.g., labs and greenhouses for early-generation seed production), human capacity, and funding, indicating the need for an integrated seed health strategy, not only incorporating the use of certified seed but also improving on-farm seed management and making resistant varieties accessible and available to farmers (148, 149), with careful consideration of policies, regulations, and value chain development (**Figure 1**).

In addition to gradual yield and quality decline caused by seed degeneration, rapid and devastating losses are caused by emerging and re-emerging pathogens and pests affecting RTs (**Figure 1**). Examples of emerging pathogens in RTs include *Ralstonia solanacearum*, potato cyst nematodes (PCNs) (*Globodera* spp.), and *Candidatus* Liberibacter solanacearum in potato; cassava mosaic disease (CMD) and cassava brown streak disease (CBSD) in cassava; sweetpotato virus disease (SPVD) in sweetpotato (as a persistent threat); and yam mosaic virus (YMV) in yam.

This review discusses the main phytosanitary challenges and potential solutions for RTs cultivated in the tropics for food and income generation. Above, we provide an overview of RTs in tropical regions. Below, in Section 2, we present the phytosanitary challenges, focusing on diseases, including those caused by nematodes, for each of the RTs; in Section 3, we identify current approaches and their limitations to address the challenges identified in Section 2; in Section 4, we look into the future and discuss new approaches and potential new challenges; and in Section 5, we provide conclusions and an outlook.

2. CURRENT PHYTOSANITARY CHALLENGES

2.1. Cassava

A wide diversity of diseases affect cassava and can readily be carried from one crop to the next if management measures are not applied. Many of these diseases have large continental or pantropical distributions and cause losses equivalent to billions of US dollars annually (78). One of the most important examples of a pathogen damaging cassava wherever it is grown is cassava bacterial blight (*Xanthomonas axonopodis* pv. *manihotis*), which causes necrotic water-soaked lesions on cassava leaves that coalesce and in severe cases result in stem dieback (85). Causal bacteria can be spread locally by farm tools or rain splash, but infected stems also facilitate long-distance movement, and this was the cause of continental spread from Latin America to Africa and Asia in the 1970s (161). Cassava anthracnose (*Colletotrichum gloeosporioides* f. sp. *manihotis*) is a pantropical fungal disease that causes stem cankers and is therefore readily spread through infected planting material. Heavy rainfall can disperse spores, leading to the spread of infection, and a heteropteran insect (*Pseudotheraptus devastans*) has also been implicated as a local vector. Cassava witches' broom disease (CWBD) is currently one of the most damaging pathogens affecting cassava and has spread widely through Southeast Asia. Although early studies suggested the causal agent was a phytoplasma, it has now been definitively proven that CWBD is caused by a basidiomycete fungus

(*Ceratobasidium* sp.) very closely related to *Ceratobasidium theobromae*, which causes similar symptoms in cacao (77). The threat of wider spread of CWBD has already been confirmed by reports of the disease, confirmed by molecular analysis, from border areas of Amapá Province in northern Brazil and southeastern French Guiana (4).

More than 25 viruses have been reported to infect cassava, of which sixteen have been recorded from Africa (76, 81), although the cassava mosaic begomoviruses (CMBs) and cassava brown streak ipomoviruses (CBSIs) are the only groups with significant economic importance. CMB species have also been present for several decades in South Asia but have only been spreading through Southeast Asia during the past decade (164). Cassava common mosaic virus and cassava vein mosaic virus are locally important in parts of Latin America (26, 81), but the viruses are generally less damaging in Latin America than they are in Africa or Asia. All cassava-infecting viruses described to date are efficiently propagated through stem cuttings, and this fact coupled with the greater difficulty of treating virus infections means that these are the pathogens that pose the greatest phytosanitary challenge to cassava seed production. In Africa, cassava viruses cause annual losses of more than US$1 billion annually (80). CMD caused by CMBs occurs throughout sub-Saharan Africa, whereas CBSD caused by CBSIs is restricted to parts of East, Central, and Southern Africa. Since the spread of an unusually severe epidemic of CMD through East and Central Africa in the 1990s–2000s was effectively tackled through the deployment of resistant varieties (40), greater focus has been directed to addressing new spread of CBSD in previously unaffected parts of East, Central, and Southern Africa. A whitefly vector (*Bemisia tabaci*) transmits both CMBs and CBSIs, although differences in the transmission mechanism for the two diseases, and more obvious symptom expression for CMD, mean that stem cuttings are a more important means of disease spread for CBSD than they are for CMD.

2.2. Potato

In tropical countries, potatoes face a myriad of phytosanitary challenges, with more than 40 major threats identified (see compendia such as 163). Among these, soilborne and seedborne pathogens causing seed degeneration deserve special attention. For example, purple top (a disease associated with the presence of phytoplasmas) (e.g., 28) and zebra chip (*Candidatus* Liberibacter solanacearum transmitted by the potato psyllid *Bactericera cockerelli*) are two devastating diseases spreading in Colombia, Ecuador, and Peru. In these countries, purple top disease can cause up to 100% yield loss (24, 27, 106). Bacterial wilt (*R. solanacearum*) has devastated potato production in various African countries (e.g., Kenya and Rwanda) (130, 157). Other critical pathogens include *Synchytrium endobioticum* (12, 158), *Spongospora subterranea* f. sp. *subterranea* (55), Potato virus Y (51, 150), and Potato virus V (50). *Phytophthora infestans* is a reemergent pathogen with populations becoming more aggressive and resistant to systemic fungicides, as seen with the spread of the 13_A2 clonal lineage with significant losses in both seed and ware potato production (49, 67, 109, 127).

Climate change may significantly affect the presence of diseases in potatoes in tropical countries (102). For example, in climate change scenarios, higher-elevation locations in the tropics that could have previously been sources of lower-disease potato seeds may no longer play that role (135). This may be associated with the decline of virus autoinfection (Potato virus Y or Potato leaf roll virus) at higher elevations and increased presence of insect vectors like aphids (e.g., *Myzus persicae*) due to higher temperatures (17, 162). Moreover, increasing temperatures and shifts in precipitation can alter the distribution and increase the reproduction rates of existing and new pathogens while also accelerating their adaptation to changing conditions (41, 134). For example, the incidence of *Meloidogyne javanica* and *Meloidogyne incognita* is expected to increase primarily due to increasing temperatures (162). Climate change is expected to have varying impacts on the presence of phytosanitary challenges and will not affect the risk of all pathogen species in the same manner (86).

Seed potatoes are a critical input for potato production worldwide, significantly influencing both the cost and quality of the crop. However, their availability and access remain major challenges, particularly in LMICs (148). These challenges have led to seed potato shortages, encouraging the movement of seed potatoes within countries and across regions and continents. Unfortunately, such movement increases the risk of pathogen spread, including quarantine diseases, which many LMICs lack the capacity to effectively manage. For example, the bacterial wilt pathogens have spread unchecked in tropical regions. Viruses, especially Potato virus Y (119), are increasingly prevalent. In East and Southern Africa, new diseases such as blackleg and soft rots—primarily caused by *Pectobacterium* and *Dickeya* spp., collectively known as soft rot Pectobacteriaceae (SRP), have been identified as a major constraint in potato production. SRPs infect stems and damage tubers during growth, transport, and storage (31). In 2013, SRPs were listed among the top ten most important phytopathogenic bacteria (90). Globally, key pathogenic SRPs affecting potato include *Dickeya dianthicola*, *Dickeya solani*, *Pectobacterium atrosepticum*, *Pectobacterium brasiliense*, *Pectobacterium carotovorum*, and *Pectobacterium parmentieri* (38, 65, 151, 159). SRP has been documented in several African countries, including Algeria, Kenya, Morocco, South Africa, and Zimbabwe (108, 121, 143). However, the distribution and identity of SRPs in many African countries remain largely unknown.

The PCNs *Globodera rostochiensis* (20, 120) and *Globodera pallida* (125, 144) are quarantine organisms in more than 100 countries and are becoming important pests of potatoes globally. PCNs were recently reported in Kenya in 2015 (104), Rwanda in 2019 (112), Uganda in 2020 (35), and South Africa in 1971 (68). The status of PCNs in other countries in the region is unknown, mainly because no studies have been conducted to detect and confirm the presence of these pests. It is likely that PCNs were introduced into currently infested countries much earlier, possibly through imported potato seeds, but were unnoticed until significant damage was observed or proactive investigations by international research organizations were conducted.

2.3. Sweetpotato

SPVD is the greatest phytosanitary challenge to sweetpotato production in the tropics and globally. SPVD is caused by the synergistic interaction between the sweetpotato chlorotic stunt virus (SPCSV) and the sweetpotato feathery mottle virus (SPFMV), which can cause up to 100% yield loss (116). The warm, humid conditions in most tropical regions are conducive to the insect vectors—aphids (e.g., *Aphis gossypii*, *M. persicae*) and whiteflies (*Bemisia* sp.)—that spread the viruses. SPCSV is a crinivirus transmitted by whiteflies, and SPFMV is a potyvirus transmitted by aphids (34). Additional potyviruses as well as whitefly-transmitted begomoviruses can further aggravate the disease. These phytosanitary issues are compounded by in-country and transboundary movement of planting material.

Fungal and bacterial diseases are less important in sweetpotato compared to viruses, but they can pose a significant phytosanitary threat when conditions are favorable. Fungal pathogens like *Alternaria bataticola*, responsible for Alternaria leaf and stem blight, *Sphaceloma batatas*, responsible for leaf and stem scab, and *Diaporthe destruens*, responsible for foot rot, can cause outbreaks under favorable environmental conditions (34). Bacterial diseases, such as bacterial stem and root rot caused by *Erwinia chrysanthemi* and foot rot caused by *D. destruens*, have become major production constraints because they destroy plants and fleshy roots and spread through planting materials (34).

2.4. Yam

Yams are susceptible to various pests and diseases, the distribution of which varies by geographic region and type of yam species (99). Viruses and nematodes are the most damaging, as they are tuber-borne and cause seed degeneration, impacting yield and quality, particularly in West Africa.

Approximately 20 viruses have been reported to infect yam globally (86a). YMV and yam mild mosaic virus, both of genus *Potyvirus*, and several members of the genus *Badnavirus*, generically referred to as yam badnaviruses (YBVs) (129), were the most widespread of more than 15 viruses reported to infect yams. Chinese yam necrotic mosaic virus, yam chlorotic mosaic virus, yam chlorotic necrosis virus, and Japanese YMV were reported from South and East Asia (86a). Several cryptic viruses were recently detected in various species of yams, including yam latent virus in China, Yam virus Y, and Dioscorea mosaic–associated virus in *D. rotundata-cayenensis* and *D. alata* in West Africa and the Caribbean. YMV reduces tuber yields by about 40% in *D. rotundata-cayenensis* and is the most economically important virus of yams in West Africa.

Root-knot nematodes (*Meloidogyne* spp.) and lesion nematodes (*Scutellonema* spp., *Pratylenchus* spp.) are widespread in yam production regions (69). Various *Meloidogyne* species have been recorded infecting yam, mostly *M. incognita*, *M. javanica*, and *Meloidogyne arenaria*, but recently the highly aggressive species *Meloidogyne enterolobii* was also recorded in West Africa (70). Lesion nematode (*Scutellonema bradys*) infection results in dry rot, with the causal species endemic to West Africa and detected in Asia and the Americas. *Pratylenchus coffeae* in Central America and *Pratylenchus sudanensis* in East Africa cause similar symptoms of dry rot and degeneration of tubers and affect seed viability and marketability (21).

Several factors contribute to yam vulnerability to biotic threats, including the long crop cycle (7–10 months) (99). Vegetative propagation perpetuates virus and nematode infestations, as farmers often reuse tubers. The quality of seed sold in the markets is the same quality of farmer-saved seeds due to limited or lack of quality seed yam production systems in West Africa. Furthermore, yams undergo a dormancy period of 2–3 months in storage, making them susceptible to pest invasions and fungal infections before replanting, exacerbating storage losses. A study in Nigeria estimated that farmers source up to 30% of their seed from markets because of the loss of saved seeds to seed degeneration (141). Decades of traditional exchange of planting materials among communities and porous borders in West Africa have facilitated the spread of tuber-borne pests and pathogens between regions and seasons to the extent that major pest and disease profiles across all countries in the Yam belt are similar. Effective management of pests and diseases is essential for yam sustainability, particularly in West Africa, where this crop is vital for food security.

3. ADDRESSING THE CHALLENGES: CURRENT APPROACHES AND LIMITATIONS

Phytosanitary challenges of RTs are managed, ideally, by an integrated strategy (148, 149) that includes (*a*) improving access and availability to clean seed by strengthening the formal seed sector; (*b*) breeding for host resistance and disseminating resistant varieties; (*c*) strengthening on-farm seed management; and (*d*) designing effective policies and regulations to deal with seedborne diseases (**Figure 1**).

3.1. Improving Access and Availability of Clean Seed by Strengthening the Formal Seed Sector

Vegetative propagation of RTs exacerbates the spread and incidence of seedborne diseases because infected planting material acts as a reservoir for pests and pathogens, which are often symptomless, allowing them to go unnoticed, persisting and spreading from season to season (57, 78, 148).

QUALITY DECLARED SEED

Quality declared seed (QDS) is a semiformal system that ensures farmers' access to seeds of acceptable quality without the stringent requirements of the formal seed system (44). Regulatory authorities inspect only a small portion of the seed production area, and seed producers or associations oversee quality assurance for the rest. The system is particularly valuable for vegetatively propagated crops (VPCs) which have received minimal attention from the private seed sector. It promotes the production of clean, disease-free planting materials, enhancing the physiological and phytosanitary quality of seed, especially for smallholder farmers. Countries such as Ethiopia (61) and Tanzania (155) have adopted the QDS system for VPCs, with others following suit. A key limitation is that QDS seed trade is restricted to the locality or district of production, which may limit broader dissemination and impact.

For effective country-level control of the propagation of RT diseases through seed, it has been recognized that there is a significant value in setting up a formal seed system (145) in which seed quality is managed at all levels by regulatory authorities.

Formal seed systems for RTs are like those of sexually propagated crops, such as grains and legumes, and follow the same structure as the formal seed systems in high-income countries (48, 79). They include production of seed at prebasic (i.e., breeder), basic (i.e., foundation), and certified levels. In these systems, nuclear material (base stock) of improved varieties is obtained from virus-indexed tissue culture material. Early-generation seed is propagated in either the laboratory or various forms of screenhouse/screen tunnels before it is advanced for further multiplication in isolated fields. Quality is supervised at all levels through inspections by regulatory authorities, or farmers can self-declare the quality of their seed following the quality declared seed (QDS) approach (see the sidebar titled Quality Declared Seed). Several countries have started embracing the QDS approach. For example, Tanzania already has guidelines for cassava, potato, and sweetpotato (155).

Molecular diagnostics are used at the highest level of the seed system to test for major viruses. Regulatory authorities in several countries make use of Seed Tracker (**https://www.seedtracker.org**) (73), an application developed for surveillance of the cassava and sweetpotato planting material value chains, which enables seed producers to register their fields and provides the tools for regulatory authorities to conduct field inspections. The resulting certified seed can be used by farmers to replace their seed lot entirely (as in high-income countries) or partially, a practice that has been shown to be promising for smallholder potato production (107, 113).

In cassava, examples of formal seed systems include those in Nigeria with the National Agricultural Seed Council and in Tanzania with the Official Seed Certification Institute. Elements of improved cassava seed phytosanitary management have been used elsewhere, including tissue culture and virus indexing for propagating healthy material of new varieties and tunnel or screenhouse propagation of early-generation seed, such as in Vietnam for CMD management (154) and Brazil through the Reniva Project (36).

In potato, new rapid multiplication technologies have been developed to make seed production and certification more cost-effective. For example, apical rooted cuttings have been used with high success to obtain high-quality certified seed in some LMICs (60, 160), including Kenya and Nigeria, where this type of planting material has been incorporated into the seed potato certification process (45). Also, aeroponics has been implemented worldwide to supply high-quality seed potatoes. In Andean countries, for example, this technology has been implemented for almost two decades but with limited success, mainly because of the need for sophisticated irrigation equipment, an unreliable electricity supply, and the risk of irreversible plant damage caused by vascular pathogens or nutritional imbalance (93).

In tropical climates, sweetpotato is multiplied through cuttings and the major problem in clean seed production is the ubiquitous presence of symptomless viruses that rapidly reinfect planting material and cannot be recognized reliably through symptoms on plants. Reliable virus detection is only possible through biological indicator plants, use of which is too time consuming to be practical in a seed system, or sensitive molecular methods, which are mostly too costly to be sustainable. Progress has been made with the development of cheaper sensitive molecular detection methods that can be used directly in the field, such as loop-mediated isothermal amplification (LAMP) (166), and could be used cost-effectively to confirm virus absence in early generations of seed. Still, rapid multiplication of cuttings under protected structure derived from certified clean nuclear in vitro material is critical. Technologies such as sandponics (167) and the use of low-cost temporary net tunnels (114) combined with ratooning (115) can lead to improved multiplication rates and affordable protected structures for seed production.

In yam, cultivars with durable resistance have not been identified for viruses and nematodes endemic in West Africa. Therefore, seeds of most popular yams, including landraces and released varieties, are susceptible to viruses and nematodes in West Africa. The management focus has been on providing pest- and pathogen-free seed yam. In the 1970s, efforts were focused on improving the quality of farmer-saved seed and supporting graded yam production in specialized seed yam systems in Anambra state in Nigeria (100). Adapted yam minisett techniques (AYMT) were popularized to control yam nematodes and rot-causing fungi in West Africa. AYMT involves treating minisetts with fungicide and insecticide to protect yams from soilborne pests and improve plant performance. However, managing virus diseases has been a major challenge due to the lack of systems for sustainably generating virus-free yams. Since YMV is endemic in West Africa, the propagation of virus-free yams is mired in the challenge of rapid reinfection with YMV in the field. There have been investments since 2011 in improving yam seed systems in West Africa through an initiative termed Yam Improvement for Income and Food Security in West Africa (91, 97). The challenge of seed multiplication was addressed through technologies such as temporary-immersion bioreactors for in vitro propagation of virus-free yam (13), which were then used in aeroponics or hydroponics to generate shoots from which vines and single leaf-buds were harvested to generate mini seed tubers (mini seed yams of ∼10 g to ∼1 kg) for seed yam production (6, 13). The development of appropriate diagnostics for the sensitive detection of viruses in tubers and the establishment of quality management protocols, which were used to regulate quality seed production efforts by the regulatory agencies, has ushered in a new beginning in producing quality seed yams in West Africa (91, 110, 133). These technologies are now allowing an almost 1:300 rate per single stock of yam of virus- and nematode-free seed yam production of popular cultivars in Nigeria and Ghana (5) and are being scaled to other regions in West Africa (97). However, reinfection with viruses in the open field has remained a significant challenge.

Certified seed of RTs produced through formal seed systems has been shown to deliver a yield benefit of up to 135% compared to farmer-saved seed of the same variety in cassava in Tanzania (172), 52% in potato in Ecuador (29), 30% in sweetpotato in seven countries (57), and at least 50% in yam in Nigeria (98). However, seed systems of RTs in LMICs in the tropics continue to be managed informally in almost all territories where the crops are grown, with the consequence that phytosanitary challenges are generally not addressed at the system level. The process of seed certification requires several years of seed multiplication under field conditions, which significantly increases the costs of seed production, a reason this approach is rarely being used in LMICs. It is estimated that less than 10% of the seed of RTs used by small-scale farmers in LMICs is certified (148). Limited use of certified seed is largely due to its poor availability, high prices, deficient distribution networks, and limited awareness among farmers about certified seed and varietal choices. Although access to quality-assured seed is gradually improving, the seed sector requires significant reforms to ensure broader and more affordable access to quality seed material. Furthermore, the seed market plays a vital role in commercial RT production by influencing pricing, marketing, value chain competitiveness, and the quality of the final product. When the demand for a specific variety increases, it becomes essential to closely monitor seed market dynamics to ensure sustainability. Recent research has shown that these markets play an important role in seed dissemination (136, 137).

3.2. Breeding for Host Resistance and Dissemination of Resistant Varieties

Resistant varieties can be an effective approach to managing phytosanitary problems in RTs. In sweetpotato, significant progress has been made in developing SPVD-resistant varieties that could drastically reduce yield loss. For instance, breeding schemes in sub-Saharan Africa have been able to develop resistant varieties with high yield, low or no SPVD symptoms, and low virus titer (103). In yam, efforts are ongoing to identify durable resistance to YMV through breeding efforts for sustainable management of YMV in West Africa (2). In potato, scientists have identified and obtained genes that confer resistance to late blight from both intraspecific and interspecific sources. These resistance genes can be isolated using molecular techniques and then integrated into potato varieties through methods such as somatic hybridization or recombinant DNA technology. Cutting-edge approaches, including CRISPR gene editing, RNA-based gene silencing, and gene pyramiding, offer powerful strategies for combating *P. infestans* (16). In cassava, breeding for resistance work has focused primarily on the two major viral diseases: CMD and CBSD. For CMD, single gene and multigenic sources of resistance have been effectively combined to produce near-immune varieties (47), and these were widely disseminated in East and Central Africa to tackle the severe CMD pandemic of the 1990s/early 2000s (82). It has proven more difficult to develop high levels of resistance to CBSD. Efforts to apply transgenic approaches have been partially successful, although the release of transformed varieties has been held back by both technical and regulatory constraints (18). Current efforts to tackle CBSD in affected parts of East, Central, and Southern Africa therefore rely on the dissemination of partially resistant or tolerant varieties, coupled with the application of strong phytosanitary controls applied through seed systems (79).

However, in some cases, as for *Candidatus* Liberibacter solanacearum in potato, resistant varieties have not been developed yet and it is unclear whether host resistance is available (168). Other economically important pathogens and pests of RTs for which there is no resistance available or for which resistant varieties have not yet been developed and disseminated include weevils in sweetpotato, cassava green mite and whiteflies in cassava, and YMV in yam, particularly *Dioscorea rotundata*. Similarly, dissemination of improved varieties remains low, which can be explained mainly by a poor understanding of varietal demands by different types of farmers, ineffective seed delivery pathways, and ineffective policies and regulations (95a).

3.3. On-Farm Seed Management

If farmers have no access to sources of clean seed, simple seed selection measures (positive selection, i.e., selecting seed from asymptomatic plants, or negative selection, i.e., avoiding seed from severely symptomatic plants), among many other practices (e.g., 105, 107), can be applied to minimize the likelihood of diseases being carried on planting material from a parent crop to a new planting. This is particularly effective when symptoms of diseases or pests are clear and pronounced, such as those caused by certain arthropod pests and viral, bacterial, and fungal pathogens. In cassava, CMD has clear, characteristic symptoms that aid in discrimination between healthy and infected plants, and positive selection has been demonstrated to provide a significant benefit for the yield of the subsequent crop (88). By contrast, CBSD symptoms are much less obvious (111), making it difficult for farmers to select clean planting material through visual inspections. In potato, for farmers with uncertain markets and high-risk economies, positive selection is an affordable and readily available option compared to regular selection of seed (23). This method requires no monetary investment, making it accessible to all potato growers, including those without access to high-quality seeds. Furthermore, it is particularly well suited for traditional varieties and unrecognized cultivars that cannot be propagated through official channels (59). In yam, positive and negative selection were shown to be effective in salvaging better-quality planting material. However, this method is only effective in fields planted with clean seed, followed by measures to minimize reinfection to avoid saturation of disease/pest incidence.

Combining several control strategies, including resistant varieties, clean seed systems, and on-farm management, may be a more effective approach for addressing phytosanitary challenges in RTs (148, 149), such as SPVD in sweetpotato (116) and seed degeneration caused by several pathogens in potato (107, 148). In sweetpotato, most bacterial and fungal diseases can be controlled through strategies such as the use of resistant cultivars, field sanitation, disease-free planting material, and rotation (33). However, for pathogens like *R. solanacearum*, *Pectobacterium*, and *Dickeya* spp. in potato, effective control methods are lacking, making their eradication or management extremely difficult once they have been established in a production area. In some cases, farmers have no other option than to abandon their fields because of the high incidence and severity of such diseases.

3.4. Policies and Regulations to Deal with Seedborne Diseases

RTs share many of the same phytosanitary challenges as planting material for other crops and, as a result, benefit from many of the same policies and regulations designed to address these challenges. In many smallholder production systems in LMICs, the issue is that, even where farmers are aware of the benefits of quality planting material, their actual demand remains low (126, 131). This may be broadly explained by farmers' expectations of low and variable returns from investment in quality planting material over space and time, the high cost of seed, which escalates input costs, and unavailability of quality seed. It may also be explained by the common practice of saving seed from previous harvest and imperfections in the market for planting material (19, 170).

Specifically, farmers who want to obtain planting material may know less about its phytosanitary health than the provider—whether the provider is an input retailer, a farmer cooperative, or a neighboring farmer—potentially leading to nonoptimal or inappropriate use of the planting material and the complementary inputs and management practices. Exacerbating this issue is the "credence good" nature of planting material: Even after accumulated experience over one or multiple seasons, it may not be possible for the farmer to draw any conclusions about the actual quality of the planting material (169). These market imperfections make the exchange of planting material problematic and necessitate appropriate instruments or mechanisms to reduce information asymmetries, crowd out providers of low-quality planting material, and increase the confidence with which farmers participate in the market. Policies and regulations provide a potentially useful mechanism to ensure phytosanitary health when applied in conjunction with breeding for resistance, advancing improved production techniques, and introducing farmers to best management practices for crop cultivation. Prior studies indicate that a wide range of policies can address the imperfections in markets for planting material in LMICs, typically framed in terms of public regulatory systems that certify seed quality through external oversight, inspection, and monitoring of production, packaging, and distribution (e.g., 152, 153). These systems are sometimes complemented by other, more farmer-friendly systems such as QDS (see the sidebar titled Quality

Declared Seed) or even supplanted by truthful labeling laws or quality assurance systems managed directly by the seed producer itself that operate under the credible supervision and monitoring of public regulators (58, 92, 139). These systems may also operate in conjunction with (or sometimes separately from) other policy interventions such as input distribution schemes, decentralized seed production projects, farmer training and extension programs, or other interventions operated by public and civil society actors (7, 59, 96).

But RTs also differ from other crops when it comes to phytosanitary challenges and their associated policy and regulatory remedies. Few LMICs have paid adequate attention to the formulation and implementation of phytosanitary policies and regulations for RTs that account for issues such as low multiplication rates, bulkiness and perishability, and high susceptibility to pests and disease (96, 146). Nor have they addressed the intrinsically integrated and inseparable nature of formal and informal systems in smallholder production systems (83). These issues tend to limit the realization of the potential benefits associated with phytosanitary health in RT planting material.

Finally, public investment in capacity development for seed providers—especially small-scale rural entrepreneurs, farmer-based organizations, and cooperatives—is another essential policy opportunity for improving the phytosanitary health of RT planting material in LMICs. This includes investment in training in regulatory standards; appropriate production practices; pest and disease management; storage, packaging, and transportation; and business and enterprise management. Of course, these policies and regulatory options are not immediate panaceas for RT seed sector development or RT phytosanitary health. Long-term investment in the formulation and implementation of crop- and country-specific policies and regulations are necessary. It is also important to recognize that there are often winners and losers in policy and regulatory reform processes, potentially resulting in contestation between seed sector actors. But given the current situation in RT seed sector development in many LMICs, it might be reasonable to assume that any growth that integrates farmer-based systems with formal seed systems, sensible regulation, and strategic public investment will ultimately improve the phytosanitary health of RT seed and generate productivity- and welfare-improving outcomes for farmers and consumers who depend on RTs.

4. LOOKING INTO THE FUTURE: NEW CHALLENGES AND THE NEED FOR NEW APPROACHES

4.1. Responding to Technical Challenges Across Root and Tuber Crops

Because RTs play a major role in food security in LMICs, especially in smallholder production systems, designing and implementing a coordinated approach to assessing and prioritizing the risks from new and emerging pathogens is necessary to prevent large-scale spread and losses as well as respond to existing pathogens (**Figure 1**). This is particularly important because the overall state of plant health of cassava and potato is declining, especially in Sub-Saharan Africa (cassava) and East Asia (potato) (1), and similar trends are observed for yam and sweetpotato in South America, Africa, and Asia. Key diseases that need to be addressed include CWBD in Southeast Asia and CBSD in East, Central, and Southern Africa; PCN (94), blackleg, and soft rot (121) in Sub-Saharan Africa; zebra chip in South America (106); and foot rot in East and Southeast Asia, where it is an emerging and rapidly spreading problem (52, 87, 122), whereas the significance of sweetpotato begomoviruses is being more broadly realized (165 and references therein). In yam, we have observed an increasing incidence of leaf-feeding insects, such as *Spodoptera* sp., in the early stage of plant growth in farmers' fields and tuber beetles, particularly for yams grown along the riverbeds in certain areas in Ghana and Nigeria.

Significant improvements in RT productivity worldwide could be achieved by strengthening farmer knowledge of the main pest and disease constraints and co-creating knowledge (156) and

ROOTS, TUBERS, AND BANANAS EAST AFRICA GERMPLASM EXCHANGE LABORATORY

The Roots, Tubers, and Bananas East Africa Germplasm Exchange Laboratory (RTB-EAGEL) (30) is a partnership between the Kenya Plant Health Inspectorate Service (KEPHIS), International Institute of Tropical Agriculture (IITA), and International Potato Center (CIP by its Spanish acronym), funded by German Corporation for International Cooperation (GIZ by its acronym in German) through CGIAR's Crops to End Hunger (CtEH) initiative. RTB-EAGEL offers pathogen diagnostics, virus elimination, in vitro culture, and germplasm exchange of bananas, cassava, potato, sweetpotato, and yams, and promotes regional research and knowledge sharing. Strategically hosted by KEPHIS, the laboratory capitalizes on KEPHIS's role as the Common Market for Eastern and Southern Africa (COMESA) regional reference laboratory and Center of Phytosanitary Excellence (COPE).

effective management practices with farmers and other stakeholders. With the rise of artificial intelligence and mobile apps, there are new opportunities to manage pests and diseases in line with farmers' socio-ecological contexts. For example, the use of WhatsApp with the integration of a chatbot can contribute to management. WhatsApp has already been used for the dissemination of farmer-to-farmer videos in areas where extension agents are not present (3, 15). Other examples include digital tools such as PlantVillage Nuru (72) that allow major cassava, potato, and sweetpotato pests and diseases to be identified, but farmer awareness about such support tools remains very limited. Similarly, in regions where the impacts of RT pests and diseases are particularly high, there is a need for increased awareness among farmers of the benefits of growing clean seed of improved varieties and applying other management practices, as demonstrated for CBSD in cassava in Tanzania (172) and late blight in potato in Peru (123, 124).

Strengthening stakeholder knowledge and capacity along the value chain, particularly in pest and disease diagnostics, and broadening the network of laboratories with the capacity to undertake comprehensive diagnostics and indexing activities, as well as promoting the exchange of improved germplasm, are essential for addressing existing and new phytosanitary challenges in RTs. For example, the three largest collections of cassava germplasm (Alliance of Bioversity International in Colombia, the Brazilian Agricultural Research Corporation in Brazil, and the International Institute of Tropical Agriculture in Nigeria) follow standard operating procedures for germplasm maintenance and exchange, including virus indexing, with the aim of keeping any risks of spreading pests and diseases between countries and continents to an absolute minimum. Recently, the launch of a regional initiative called RTB EAGEL (Roots, Tubers, and Bananas East Africa Germplasm Exchange Laboratory) (see the sidebar titled Roots, Tubers, and Bananas East Africa Germplasm Exchange Laboratory) enabled stakeholders to quickly access improved germplasm with resistance to key diseases and to receive training on diagnostics and appropriate management methods, slowing spread and mitigating the impact of these threats. However, the continued increase in levels of international travel means that further pest and disease introductions are inevitable. These threats should be mitigated, however, by encouraging major RT-producing countries to place a greater emphasis on establishing early warning systems with concomitant rapid response strategies (25).

In addition to strengthening stakeholder knowledge, further research will be required on newly described pathogens; the ongoing threat of wider spread of pathogens such as CWBD in cassava and PCN, blackleg, soft rot, and zebra chip in potato; and the effect of climate change on existing and emergent pathogens. In parallel, researchers and practitioners can work to improve molecular diagnostics for early disease detection and routine seed production. Faster development of markers for real-time polymerase chain reaction or LAMP could support timely interventions.

Developing such interventions will be based on agroecological principles and practices, such as soil health and crop diversification, with the potential to increase the resilience of cropping systems against pathogens. Finally, genebanks and breeding programs must continue discovering new genes and developing improved varieties with disease resistance as well as resilience to climate change–related stresses like drought, heat, and cold. For example, the advancements in yam genetic transformation and genome editing based on CRISPR/Cas9 system protocols will provide opportunities for yam improvement (142).

Once new varieties are developed, new approaches to strengthening seed systems could be explored, including effective seed delivery pathways and seed business models such as decentralized seed multipliers or seed banks, to enhance the distribution of quality seed of improved or locally adapted varieties to target locations and farmers. Methods like impact network analysis can help identify key entry points for distributing seed or preventing the spread of pests (42, 43, 53). Another method, means-end chain analysis, can be used to understand the incentives for using clean seed and new varieties (e.g., 117, 118) and improve their delivery and adoption.

Once a seed movement network has been characterized by Seed Tracker (73), seed tracing (66), or related methods, the potential for it to act as an epidemic or invasion network for seedborne pathogens and pests can also be understood, along with potential priorities for management of the network (10, 22, 43). Farms are linked in epidemic networks through both seed movement and farm-to-farm spread through mechanisms such as vector flight and wind movement of spores (10, 171). A key factor in within-farm epidemics is the role of external inoculum (149), highlighting the importance of evaluating regional epidemics, and the potential to identify locations where activities to promote management, such as on-farm seed selection, are likely to be most successful (23). When the occurrence of disasters may exacerbate the spread of seedborne pathogens (41), integrating information about national plant health risk in humanitarian decision-making can support better responses (101). At a national scale, understanding seed networks can contribute to an integrated seed health strategy combining clean seed, on-farm management, and use of resistant varieties (12). Understanding epidemics of seedborne pathogens is also important for decision-making on how to establish QDS standards (see the sidebar titled Quality Declared Seed) that are lenient enough to be practical but strict enough to limit epidemics (32). Modeling has been used as a tool for optimizing cassava seed system management approaches (8) and providing decision support tools (11). Challenges remain in validating these tools across RT systems and making them user-friendly enough that they can be widely adopted by national seed system actors.

The overuse of pesticides in RTs is in general not an issue, except in potato production, where pesticide use continues to rise because of phytosanitary challenges such as late blight. Although research institutes are promoting rational pesticide use, agrochemical stores, where most farmers seek advice, are often overlooked. A study in the Andes showed that more than 80% of recommendations from these stores failed to address phytosanitary problems adequately (140). The improper use of pesticides not only impacts public health but also affects ecosystem services and harms beneficial insects and pollinators, making this a critical issue for researchers and practitioners to address.

4.2. Policies and Regulations

In recent years, several LMICs in tropical areas have undertaken seed sector reforms that may affect access to and availability of quality planting material for RTs (138). Although most countries have focused primarily on extending their formal seed certification systems to RTs, some have recognized the need for more holistic policy remedies, for example, improving the coordination and integration of informal farmer-based seed systems with formal seed systems, including research, regulation, and extension services (14). But formulating and implementing policies and regulations for integrated seed sector development requires considerable innovation beyond standard certification systems. There are several innovations in policy and regulation that can potentially address phytosanitary health in planting material of RTs. These innovations are specific to the crop, country, and context in which they are applied and should not be interpreted as universal recommendations. They include opening RT seed markets to new actors, recognizing multiple seed classes, decentralizing regulatory functions, introducing seed traceability systems, targeting public subsidies, promoting international trade, and investing in farmers themselves.

A first-order policy innovation worth considering in many countries is simply lifting constraints on who can produce and distribute RT planting material. Many countries have effectively criminalized the informal trade in noncertified RT seed, whereas others have set standards for education, business size, or other requirements (39, 96). These laws and standards impede efforts to professionalize farmer-based seed systems and integrate them with public research organizations, commercial seed producers, financial services providers, and other actors in the seed value chain. A simple remedy is to recognize the de facto importance of diverse seed providers. A related policy innovation is the introduction of multiple seed classes, informing farmers about the phytosanitary health of the planting material they seek to purchase. Policies and regulations that recognize multiple classes—certified, quality-declared (see the sidebar titled Quality Declared Seed), farmer-produced, and other classes—can reduce the barriers to entry and encourage seed producers to compete based on product differentiation, quality, price, packaging, labeling, after-sales services, and other variables. More entrants into the market can, in turn, stimulate growth, increase accessibility, and encourage further product differentiation for specific attributes such as pest and disease resistance or consumption and processing characteristics.

Another policy innovation is to prioritize public investment for quality assurance where it matters most in the RT seed value chain: in the earliest generations of seed production (37, 54, 138). Improving the phytosanitary health of the base material used in seed production can significantly reduce pest and disease prevalence and increase the supply of high-quality material to seed providers further down the value chain and closer to farmers themselves. A related policy innovation follows the same subsidiarity principle, i.e., that policy solutions should be executed closest to where they will have their effect or at the lowest possible level. Given the dispersed and fragmented nature of RT seed markets in many LMICs and the perishable nature of RT seed, effective regulation is likely optimized at the point where production, exchange, and use occur. This means decentralizing regulatory functions to subnational levels and increasing the participation of farmer-based organizations and enterprises in both seed production and quality assurance functions at those levels. Countries such as Kenya and Rwanda—among others—are advancing decentralized regulatory systems and training and accreditation programs for private seed inspectors, whereas other countries such as Zambia have had such programs in place longer (95, 96). However, the extent to which such systems are applied to the RT seed sector remains unclear.

Seed traceability systems enhance these regulatory systems by allowing regulators and other value chain actors to retrace seed lots, identify sources of pests and diseases in seed, and remedy problems at the point of seed production or distribution. Traceability systems, such as Seed Tracker (73), have the added benefit of providing monitoring data on varietal turnover and quality seed use, both of which are key performance indicators for public investments in crop improvement, plant breeding, and seed delivery and have been applied to RTs such as cassava in Nigeria, Colombia, and Ghana (46, 128, 169) and sweetpotato in Ethiopia (71). There are also possibilities for using public subsidies to promote phytosanitary health in RT seed systems. Examples include production subsidies targeted at small-scale commercial seed producers that reduce their costs of production and farmer subsidies designed to reduce the price of quality seed for targeted farmers.

However, the record on producer and farmer subsidy programs for seed sector development tends to be mixed, with evidence of rent-seeking behavior, crowding out of private investment, and low social returns (56, 64). However, there is limited evidence specific to RT seed subsidies.

Phytosanitary health for RT seed may also benefit from a deepening of international trade in RT seed. There are clear and direct economic gains from trade: new markets for seed producers, lower prices for farmers, and opportunities for technology transfers between and among countries. These gains are potentially augmented by the indirect benefits of introducing new harmonized quality standards—codified in regional and global agreements on phytosanitary health and seed quality—that further expand market opportunities and the supply of quality seed while preventing the transboundary spread of pests and diseases (74). Such are the expectations among, for example, the Common Market for Eastern and Southern Africa and the Economic Community of West African States member states, although the extent to which such benefits will be realized for RTs has garnered little attention.

5. CONCLUSIONS AND OUTLOOK

Phytosanitary challenges on RTs have become more complex in recent years because of increased movement of agricultural produce from one country to another and increased migration and tourism, making food scarcer and more expensive. Farmers lose millions of dollars annually due to phytosanitary problems. Some of the RT phytosanitary pests and diseases have received international attention, as they constitute a huge constraint on production, with considerable indirect effects on trade. Rigorous seed certification and testing programs in developed countries have limited the impact of these diseases in their value chains, whereas LMICs in the tropics, especially in smallholder production systems, commonly lack these safeguards. Lack of certified seed in these countries contributes to further distribution of these pathogens via latent infections as well as quality and yield degeneration caused when farmers replant diseased planting material year after year. Phytosanitary health for RTs may also benefit from a deepening of international trade in RT seed to promote a modern and competitive seed industry, including the harmonization of global best practices shifting from ex ante controls on production processes to ex post controls on truth-in-labeling at the retail level. Efforts to manage phytosanitary challenges in LMICs should follow a systems approach that incorporates specific operational practices to reduce the likelihood of incursion, establishment, and growth of these pests and pathogens in RTs. This includes training farmers in proper production practices, including sanitation, crop rotation with nonhost plants and planting in clean soil, on-farm seed management tools, use of healthy planting materials, and use of resistant varieties. The effective implementation of these practices will be essential if the full potential for climate-resilient RTs is to be realized throughout tropical production zones.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

Jorge L. Andrade-Piedra, Kalpana Sharma, Jürgen Kroschel, and Karen A. Garrett conceptualized, wrote, reviewed, and edited the review. Kwame Ogero, Jan Kreuze, James P. Legg, P. Lava Kumar, David J. Spielman, Israel Navarrete, Willmer Perez, and Elly Atieno wrote, reviewed, and edited the review.

ACKNOWLEDGMENTS

Support for this study was provided by multiple CGIAR programs and initiatives, all of which received funding from contributors to the CGIAR Trust Fund (**https://www.cgiar.org/funders/**). These programs and initiatives include the CGIAR Seed Equal Research Initiative; the CGIAR Plant Health Research Initiative; the CGIAR Research Program on Roots, Tubers, and Bananas (RTB), led by the International Potato Center (CIP); the CGIAR Research Program on Policies, Institutions, and Markets (PIM), led by the International Food Policy Research Institute (IFPRI); and the CGIAR Breeding for Tomorrow Science Program.

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