Expansion and impact of cassava brown streak and cassava mosaic diseases in Africa: A review

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Submitted to Journal:
Frontiers in Sustainable Food Systems

Specialty Section:
Crop Biology and Sustainability

Article type:
Review Article

Manuscript ID:
1076364

Received on:
21 Oct 2022

Journal website link:
www.frontiersin.org

Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Author contribution statement

PC conceived the idea. PC and MT wrote the manuscript. PC designed the figures. All the authors contributed to the article and approved the submitted version.

Keywords

CBSD, CMD, impact, expansion, Africa

Abstract

Word count: 155

Africa produces over half of global cassava; however, the continent's average yield is below the potential yields achieved under experimental conditions. Many factors contributing to low yield include lack of quality varieties, poor soils, limited access to capital, competition for labour, as well as pests and diseases. Plant diseases are the major biotic constraints to cassava production and have caused considerable food insecurity in Africa. Although there has been some level of disease management which has contributed to the increase in cassava production, the two viral diseases: cassava mosaic disease (CMD) and cassava brown streak disease (CBSD) still claim between 30-40% and upto 70%, respectively of Africa's cassava harvest. Given the importance of the two diseases in Africa, we review the expansion of CBSD and CMD; impacts of the two diseases on food security and how they can be managed. We provide insights in the spread of the two diseases, management efforts, and future directions.

Contribution to the field

The review manuscript sets out to address the expansion of cassava brown streak disease in Africa. Cassava being an important crop in the cropping systems of many African countries, it is imperative that we review the spread and in order to address important challenges of managing the disease especially in smallholder farming enterprise. The questions that are critical are: what is driving the CBSD spread and how can this be addressed both in the short and long term

Funding statement

Citizen Economic Empowerment Commission through project number P-ZM-IEO-002 with funds provided by Africa Development Bank (AfDB).

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Abstract

Africa produces over half of global cassava; however, the continentôs average yield is below the potential yields achieved under experimental conditions. Many factors contributing to low yield include lack of quality varieties, poor soils, limited access to capital, competition for labour, as well as pests and diseases. Plant diseases are the major biotic constraints to cassava production and have caused considerable food insecurity in Africa. Although there has been some level of disease management which has contributed to the increase in cassava production, the two viral diseases: cassava mosaic disease (CMD) and cassava brown streak disease (CBSD) still claim between 30-40% and upto 70%, respectively of Africaôs cassava harvest. Given the importance of the two diseases in Africa, we review the expansion of CBSD and CMD; impacts of the two diseases on food security and how they can be managed. We provide insights in the spread of the two diseases, management efforts, and future directions.

Introduction

Cassava (*Manihot esculenta* Crantz), is an important staple crop in many African countries accounting for 61.1% of world production (Nweke, 2005; FAO STAT, 2020). In sub-Saharan Africa (SSA) there are about 18 major cassava growing countries, each producing from 1 million to over 50 million mt. The major cassava producing countries include Nigeria (59.4 million mt), DRC (31.6 million mt), Ghana (18.5 million mt), Angola (11.7 million mt), and Mozambique (8.8 million mt) (FAOSTAT, 2017) where it is grown mostly by resource-poor farmers, many of them women. Further, it is either grown as a sole crop or intercropped with vegetables, cereals (millet, maize, sorghum) or legumes (beans, cowpea) for food security.

In recent years, utilisation and processing of cassava as a raw material has increased especially in the manufacture of many industrial products such as starch, beer, flour and other bio-based products including medicine, feed, comestics and biopolymers. For example, in Mozambique and Nigeria, cassava flour has replaced up to 20% and 10% of wheat flour in bread, respectively (Salvador et al., 2014; Sawyerr, 2012). Coupled with these developments, its cultivation in many countries is transforming from subsistence to a more commercially-oriented farming enterprise. Because of this, the area under cassava production continues to expand in several African countries. Despite the expansion, productivity remains low and continues to be threatened by abiotic and biotic factors.

Among the biotic factors contributing to low productivity are diseases particularly those caused by viruses. According to Patil et al. (2015), cassava is susceptible to over 20 different viruses with the most critical caused by cassava mosaic geminiviruses (CMGs) and cassava brown streak Ipomoviruses (CBSIs).

Cassava mosaic geminiviruses (CMGs) cause cassava mosaic disease (CMD) and comprise several species of circular ssDNA viruses belonging to the genus Begomovirus, family Geminiviridae. While cassava brown streak ipomoviruses (CBSIs) cause cassava brown streak disease (CBSV) and comprise of two (+)ss RNA genomes, belonging to the genus Ipomovirus in the family Potyviridae. The CMGs and CBSIs, are not seed borne but are transmitted by the polyphagous whitefly complex *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) (Maruthi et al., 2005). CMD and CBSD are spread over long distances through planting of infected cuttings originating from diseased plants. However, the presence and abundance of infected whiteflies feeding on the plants quickens the spread from plant to plant within or adjacent fields. Symptoms of CMD and CBSD are prominent on the leaves with varying degree of mosaic and chlorosis. During the early years when CBSD was first reported, it was confined to areas less than 1000 meters above sea level (masl) along the eastern coastal line from Kenya to Mozambique and around the lake shows of lake Malawi. Over the years, the disease has significantly spread covering mid-altitude (1200-1500 masl) areas of eastern, central and southern Africa.

This review discusses the two viral diseases (CMD and CBSD), their causal agents, and their impact on cassava in Africa. We address the following topics: prevalence of CMD, which occurs in all the main cassava-growing areas, and CBSD expansion, which has been reported to occur mainly in eastern and southern Africa. We also look at the two diseases as they affect food security. We offer insights into the management of the two diseases as well as future directions.

Constraints to food security

Several constraints affect cassava production: climatic factors, soil fertility, socio-economic factors, limited access to markets, poor conditions of markets, poor main and feeder roads, high transportation costs, pests, and diseases. These factors substantially result in crop yield losses translating in millions of dollars (Tembo et al., 2017; Maruthi et al. 2004; Anderson and Morales 2005; Renkow and Byerlee 2010; Waddington et al. 2010). Because of massive yield and economic losses, agricultural scientists, extension agents, policymakers and farmers across Africa are concerned mainly due to new or recurring pest and disease problems over the last several years. Most problematic of them all are the viruses CMD and CBSD.

Since cassava is vegetatively propagated, the viruses causing the CMD and CBSD are transmitted through the cuttings used as planting material from one crop cycle to the next. Without intervention, the infection can therefore readily build up from infected plants adjacent to nearby fields particularly where there is a considerable level of vector transmission. Four virus genera are represented among the taxa that have been described as major pestsôof cassava. Out of the four, two are of economic signiýcance, namely: Ipomovirus (family Potyviridae) where cassava brown streak virus (CBSV) and Uganda cassava brown streak virus (UCBSV) belong: and the Begomovirus (family Geminiviridae) group of cassava infecting geminiviruses. This review will therefore, be restricted to a consideration of CBSIs and CMGs.

Cassava Brown Streak Disease and the causal viruses

To evaluate the threat of CBSD, it is important to understand the casual viruses, their spread, and the symptoms they cause. CBSD is caused by two (+) ssRNA species of ipomoviruses, CBSV, and the UCBSV (Mbanzibwa et al. 2009; Winter et al. 2010). Studies have shown that CBSV occurs widely and is the more aggressive virus, infecting both tolerant and susceptible cultivars as a single or mixed infection with UCBSV. Although there are only two species reported, further speciation is suggested within the UCBSV clade (Ndunguru et al., 2015). The two viruses are transmitted in a semi-persistent manner by the whitefly vector, from plant to plant. Other vectors could transmit CBSIs. Mware (2009) reported transmission of CBSV by Aleurodicus disperses albeit at low rate. Other studies have shown a highly conserved DAG motif within the CBSV, which is associated with aphid transmission (Ateka et al., 2017). The presence of the motif suggests that aphids could potentially be a vector of CBSV. Although mostly associated with cassava, CBSV can also infect other host plants, for example, *Nicotiana benthamiana* (Munganyinka et al., 2018a). Studies by Amisse et al. (2019) in Mozambique have shown that non-cassava perennial wild plant species: *Zanha africana* and *Trichodesma zeylanicum* are alternative hosts to CBSV. The plants are widely distributed in east, central and southern Africa. *Manihot carthaginensis* subsp. glaziovii, a wild cassava relative native to Brazil is also a host to CBSIs and occurs widely in Mozambique (Amisse et al., 2019).

CBSD affects all the plant parts; leaves, seed capsule, stems, and roots. The CBSIs causes yellowing of the leaves, brown streaks on the stems, and necrosis of the roots, rendering them unpalatable and unsuitable for the market (Fig. 1). In addition, they cause concentric necrotic spots on the fruit. Leaf symptoms predominantly appear as leaf chlorosis in feathery patterns along the margins of tertiary veins. In some varieties, chlorosis manifests as pin spot and may later develop into chlorotic blotches. Infected stems show brown lesions or streaks, resulting in stem dieback in severe infections. In younger stems, the streaks appear purplish. Root symptoms are characterized by formation of radial constrictions and necrotic lesions within the root.

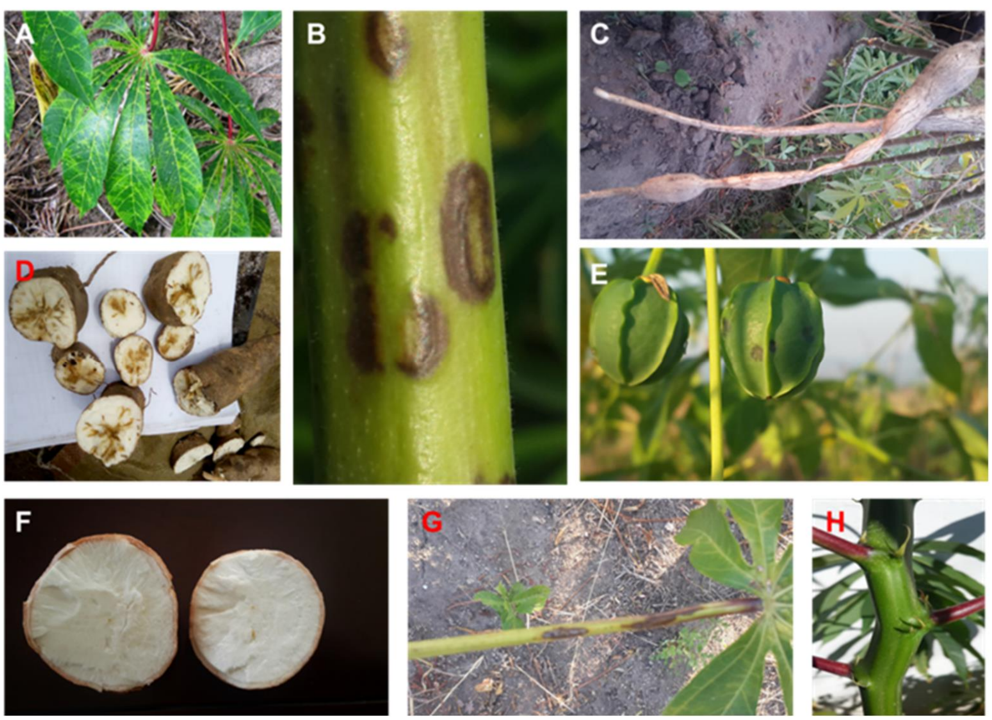

Fig 1: Symptoms of cassava brown streak disease. A. leaf symptoms of CBSD showing yellow chlorosis, associated with secondary and tertiary veins; B. Necrotic brown marks on cassava stem; C. Constrictions in tuberous roots infected with CBSD; D. Dry brown, corky necrosis in tuberous roots

associated with CBSD infection; E. Circular necrotic lesions on cassava fruit; F. Healthy roots; G. necrotic lesions on petiole; H. Healthy stem

The symptom expression depends on viruses infecting cassava, cassava variety, and environmental factors (rainfall, temperature, soil nutrient). Within the same variety, the CBSD symptoms can be observed either only on the leaves or on the stems or on the roots. In some cases they can appear on all plant parts or only on two plant parts (leaves and stems or on leaves and on the roots.

Cassava mosaic disease

Unlike CBSD, CMD is caused by any of the 11 species (commonly referred to as cassava mosaic begomovirus - CMB) in the genus Begomovirus and family Geminiviridae. The viruses include African cassava mosaic virus (ACMV), East African cassava mosaic Cameroon virus (EACMCV), Cassava mosaic Madagascar virus (CMMGV), East African cassava mosaic Kenya virus (EACMKV), East African cassava mosaic Malawi virus (EACMMV), East African cassava mosaic virus (EACMV), East African cassava mosaic virus-Uganda (EACMV-UG), East African cassava mosaic Zanzibar virus (EACMZV), South African cassava mosaic virus (SACMV) and African cassava mosaic Burkina Faso virus (ACMBFV), and Sri Lankan cassava mosaic virus (SLCMV). EACMV-UG has the most negative impact on cassava yield and contains a recombinant fragment between two distinct begomovirus species (EACMV and ACMV) from the core part of the protein gene (Zhou et al., 1997). All these viruses are transmitted persistently and retained by *B. tabaci* for much more extended periods than CBSIs, allowing for longer distance spread (Legg et al., 2011; Jeremiah, 2012).

Cassava mosaic disease causes variable leaf symptoms including mosaic, distorted and twisted leaflets, leaf narrowing, stunting, leaf chlorosis (yellow, white or pale spots) and an overall reduction in the size of leaves and plants (Fig. 2). Symptom expression depends on the variety, environmental conditions, and virus strains infecting the plants (Alabi et al., 2011). Leaf chlorosis may be pale yellow or nearly white with only a shade of green, or just noticeable paler than usual. Unlike CBSD, CMD does not cause any root necrosis; however, the disease results in reduction of root size. Further, the symptoms are enhanced when plants regenerate after being cut back to stimulate shoot development or when de-topped to provide leaves for home consumption. There is no evidence to show differences between the symptoms caused by the different cassava mosaic geminiviruses (CMGs). However, where two different CMGs are present in a plant, severe symptoms are observed than either virus alone (Chikoti, 2011). In susceptible varieties symptoms are severe than in CMD-tolerant ones.

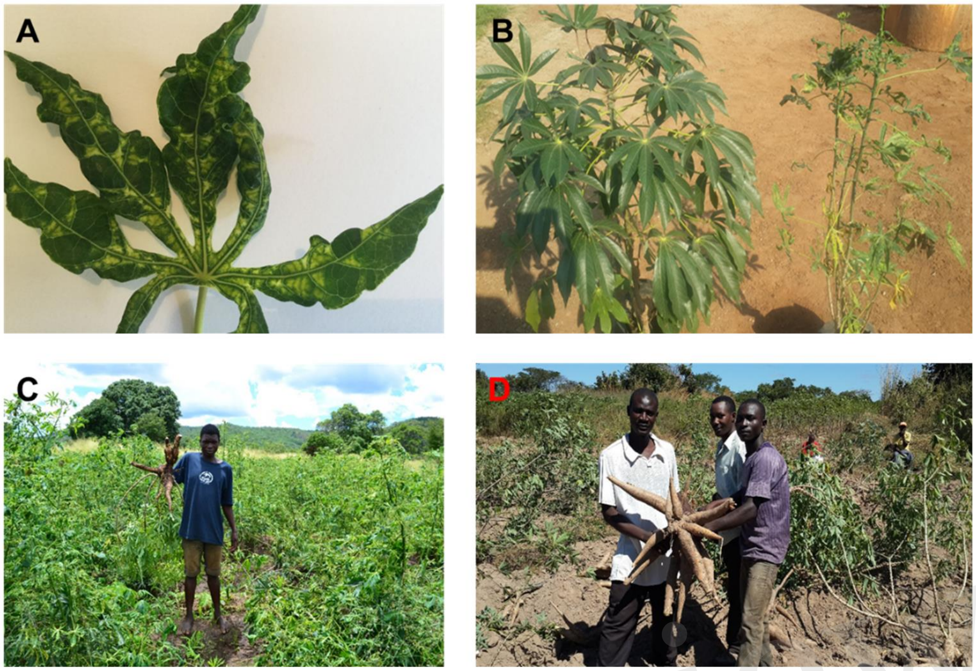

Fig. 2: Symptoms of cassava mosaic disease on cassava plants. (a) Severely affected cassava leaf; (b) a resistant variety (right) and a susceptible cassava landrace exposed to infection by CMGs (left); (c) reduced root size in plants exposed to infection by CMGs; (d) cassava roots from a resistant CMD variety

CBSD expansion and CMD status

Before 2004, CBSD was restricted to coastal East Africa and the shores of Lake Malawi. However, recent studies have shown that CBSD has spread and expanded to previously unaffected areas in many African countries (Figure 3). In Uganda surveys conducted between 2004 and 2017 showed that most areas that were previously disease free are now affected (Alicai et al., 2019). Similarly, Democratic Republic of the Congo, which borders Uganda to the east has also witnessed expansion of CBSD covering an area of more than 62,000 km^2 (Casinga et al., 2021; Muhindo et al., 2020). The expansion of CBSD has also moved southwards reaching northern parts of Zambia (Mulenga et al., 2018). Confirmed in country reports of CBSD expansion from the initial outbreak areas have been made in Rwanda (Munganyinka et al., 2018b; Nyirakanani et al., 2021), Burundi (Bigirimana et al., 2011), and south Sudan (Alicai et al., 2016). The cause of CBSD expansion is difficult to determine. However, it can be speculated that use of infected planting materials transported across long distances could be more probable than through whitefly transmission. This assertion agrees with surveys conducted in DRC close to Lake Tanganyika in Sud-Kivu, Tanganyika and Haut-Kantanga provinces, which have shown the disease, present in Sud-Kivu and Haut-Kantanga provinces (Casinga et al., unpublished) and not in Tanganyika, a province that is located between the two provinces.

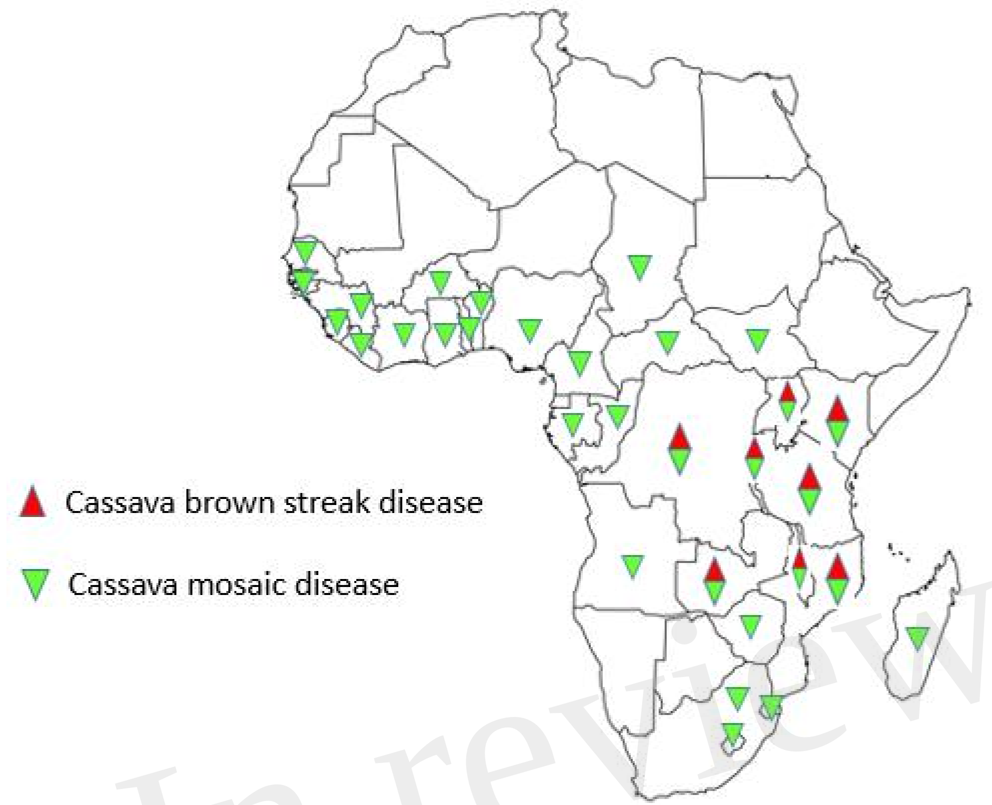

Figure 3: Distribution of cassava mosaic and cassava brown streak diseases in Africa

The ýrst comprehensive survey of CBSD was conducted in Tanzania in 1993/1994 (Legg and Raya, 1998), although this was restricted to an assessment of leaf symptoms and did not take account of stems or roots. Apart from one observation in the western mid-altitude (~1200 m) region of Tabora, CBSD was conýned to the lowland coastal plain. The average incidence for the country was 8.6%, although this rose to 36% for Mtwara region in the southeast, with three other coastal regions having incidences exceeding 19%. A more intensive survey in southern Tanzania broadly conýrmed the results of the 1993/1994 survey and highlighted the decrease in incidence from the low altitude coastal zone (29%) to the higher altitude (500ï 700 m) and Interland (7%) (Hillocks et al., 1999). The considerable variation of CBSD incidence has been reported among cassava varieties (Munganyinka et al., 2018b). For instance, in the most affected areas in which some varieties had high severities and incidences of infection, some varieties were entirely free of leaf symptoms. In a more recent report in Kenya, foliar incidence were found to range from 52.1-77.5% with root necrosis incidences from 36.7-40% (Masinde et al., 2016). It is not uncommon to find fields with 100% incidence, e.g. in Tanzania a number of fields have been reported before (Hillocks et al., 2002).

Unlike CBSD, CMD is present in all the cassava-growing countries in Africa, from East to West and from south of the Sahara to southern part of the continent (Legg et al., 2006; Ogbe et al., 2008; Chikoti et al., 2013; Alabi et al., 2011) (Figure 3). Although the disease is widely distributed on the continent, the incidence varies, and so does the disease severity. For example, in East Africa, which experienced CMD pandemic in the 1990s, the disease was very severe, and its effects were devastating.

Climate change and abundances of whitefly vectors of viral diseases

Africa has diverse ecosystems: deserts, mountains, savannas (or grasslands), forest and coastal environments with savannah being the most common. As the climate changes so does the severity of viral diseases. Climate change-driven temperature rise affects ecosystems differently. Extreme temperatures and erratic rainfall are likely to exceed the resilience limits of many ecosystems and trigger irreversible effects including that of whiteflies. Although there is no direct link between viruses affecting cassava and climate change, a correlation between whitefly abundance and temperature has been established (Saghafipour et al., 2020). Cassava is not spared as it is impacted directly by the whiteflies through whitefly damage and more so through infection of the viruses. Changes in climatic conditions in different parts of Africa in the distribution and abundance of whiteflies, and environmental suitability for plant viruses, will likely affect epidemics of CMD and CBSD. In different ecosystems, insects experience stressful temperatures (high and low) and these may affect their distribution and abundances (Cui et al., 2008). Temperature, rainfall and humidity plays an important role in the survival, development and fecundity of whiteflies. Although there is a direct correlation between temperature and whiteflies, at extreme low and high temperatures, survival of the whiteflies is affected. Optimum temperature range for *B. tabaci* (SSA1 SG3) was reported to be in the range of 20ºC to 28ºC (Aregbesola, 2018). At low (<20ºC) or high temperature (>30ºC), survivability is reduced (Saghafipour et al., 2020). This suggests that at certain point, high or low temperatures are good as they may reduce whitefly population.

The economic impact of CBSD and CMD

CBSD and CMD are the main biotic constraints to cassava production in Africa. Generally, there is lack of information on the overall estimate of the current impact of the two diseases. What is clear is that the two diseases have devastated the livelihoods of small-scale cassava farmers across the continent. A study by Hillocks et al. (2001) on CBSD in East Africa suggests yield losses of 70%. With this yield loss, CBSD represents the greatest threat to millions of cassava farmers on the continent. In monetary value, it is estimated that farmers lose up to US$100 million per year due to CBSD (Mohammed et al., 2012). Though the disease has a limited effect on the growth and appearance of plants, the dry rot in tuberous roots can render entire harvest unpalatable and unmarketable. When farmers harvest the roots, they cut out the necrotic lesions of affected tubers and discard tubers that are severely affected hoping to salvage unaffected parts. In some areas of the Great Lakes region, CBSD has resulted in total crop failure. Cultivars differ significantly in their sensitivity and response to CBSD infection. For instance in Tanzania more than 90% sensitive varieties taken from diseased stems express leaf symptoms and 12-59% (depending on the variety) had root symptoms at harvest (Hillocks et al., 2001). Not only does CBSD result in rotting of the roots in some varieties, it also reduces the number of marketable roots. In Tanzania, plants expressing foliar symptoms resulted in significant reductions in the number of roots (Ndyetabula et al., 2016). Annual yield losses in Tanzania has been estimated at 860,000 t equivalent to > US$ 51 million (Ndyetabula et al., 2016). In a study conducted in 2013 in Kenya, CBSD resulted in root loss of 24.7% translating to US$1259.50 per hectare (Masinde et al., 2016). Yield losses among small scale farmers in Malawi were estimated at 18-25 % (Gondwe et al., 2003). Not only does the disease affect root yield but root quality as well. In Uganda, high starch yield was observed at 25% in health plants compared to 21.8% in diseased plants (Nuwamanya et al., 2015).

Similarly, economic losses for CMD are known and few reports are available indicating losses from farmersô fields. The major bottleneck has been in difficulties in quantifying yield losses especially in farmersô fields. Available information indicates losses ranging between 77.5% to 97.3% (Bisimwa et al., 2015). Losses in monitory terms in East and Central Africa have been estimated at US$ 1.9ï 2.7 billion dollars per year (Patil and Fauquet, 2009). Across Africa where cassava is cultivated, Fauquet and Fargette (1990) estimated 50% yield loss in areas with CMD infection. The losses are dependent on virus type, environmental conditions, cultivar, stage of crop growth at which infection occurred, single or virus mixture causing the infection, and soil fertility (Fargette et al., 1988; Fauquet and Fargette, 1990; Spittel and van Huis, 2000). In cassava plants with single or mixed virus infection, studies on root yield have shown marked differences (Owor, 2003). For example, infection of plants with a mild strain of EACMV-UG2 resulted in minor yield reductions in comparison with healthy controls. In mixed infections, losses of up to 87% were recorded for mixed ACMV and EAMCV-UG2 infections.

Exploiting efforts to manage CBSD and CMD

Efforts to manage the CBSD and CMD through integrated approaches are being scaled up in many parts of Africa, amidst poor coordination. A few projects covering the breadth and length of Africa such as Cassava Diagnostic Project, West Africa Virus Epidemiology, and Cassava Great Lakes Initiative have attempted to manage the devastating impact of CBSD and CMD. The problem of CBSD and CMD in developing countries is exacerbated by paucity of infrastructure of extension, seed systems, and diagnostic laboratories. The inability to have critical investment in disease management has meant poor performance in the cassava sector resulting in failure to reach achievable yields. Efforts to contain the impacts of the diseases are not well coordinated in Africa, and the existing mitigation programs have little impact in addressing the disease challenges. Consequently, the Global Cassava Partnership for the 21st Century (GCP21), a recognized global organization within the cassava community, have been holding conferences with participants from affected countries. Suffice to say that the GCP 21 is a not-for-profit international alliance of 45 organizations whose aims are to fill gaps in cassava research and development in order to unlock the potential of cassava for improving food security and for increasing incomes of poor farmers through work to develop industrial products from cassava. It provides a platform where scientists share scientific information on cassava. However, most of the participants are not policymakers who can influence their respective governments to institute actions. On the other hand, the International Society for Root and Tuber Crops (ISTRC) with representation from all of the regions of the world where people either produce or consume root and tuber crops, was formed to create enabling environment to improve cassava productivity through scientific research. It has regional branches in Africa, South Pacific, and Asia. Similarly, International Institute of Tropical Agriculture (IITA) with regional hubs across Africa has over the years played a key role in managing cassava viral diseases through developing improved cassava varieties with farmer preferred traits (high yield, disease resistance and nutritional quality). It also produces and shares protocols on disease diagnosis and identification. However, all the key playersô efforts need to be strengthened.

Phytosanitation

Although phytosanitation is one technique of controlling CMD and CBSD (Thresh and Otim-Nape, 1994), it has received limited attention. Cassava is propagated using stem cuttings, and both CMD and CBSD are mainly perpetuated and disseminated in this way. As previously stated, in CBSD infected plants, symptoms may appear only on the roots or on the leaves or stems. The appearance of the symptoms makes it difficult in selecting virus-free planting materials as in some varieties the symptoms may not be clear (Ntawuruhunga and Legg, 2007). Monitoring of propagation materials for disease symptoms during the growth of the source plant can help reduce the spread of the disease. There are advantages in farmers selecting propagating material only from uninfected plants at the time the cuttings are being harvested and collected from the field. Unfortunately, most farmers are not familiar with the whole range of CBSD symptoms and tend to collect the cuttings when the source plants are almost leafless. Further farmers in communities, practice phytosanitation in isolation but where farmers cooperate, benefits have been realized. For example, communities in coastal (Mkuranga) and northwestern (Chato) of Tanzania were phytosanitation was practiced, CBSD incidence reduced from >90% to 39.1% after three years (Legg et al., 2017). The approach could also serve as a potential component for integrated cassava virus management programmes, mainly where new cassava plantations are being established in areas severely affected by CBSD.

Seed systems and disease-free planting materials

In many African countries, cassava seed system is still informal serve for a few including Nigeria, Tanzania, and Uganda (Legg et al., 2022). A functional seed system will encompass development of high yielding and disease resistant varieties and investment in infrastructure for early generation of seed. Trading in planting materials that are not certified is common occurrence across Africa. However, what is cardinal is to have the right polices and functional infrastructure. CBSD and CMD can be managed through developing and disseminating resistant or tolerant varieties. However, there have been instances where resistant varieties are not available in some countries. For instance in Zambia where CBSD was recently detected, all the landraces and improved varieties grown by the farmers were susceptible (Mulenga et al., 2018). In Tanzania, where local diseased materials were replaced with disease-free ones, 86% more yield was achieved (Legg et al., 2017). It is thought that the distribution of this clean planting material, often referred to as clean óseed,ô reduces disease pressure in communities by ensuring that the majority of crops are, at least initially, relatively disease-free (Kanju et al., 2003).

Host-Plant Resistance

One of the most effective disease management strategies to combat CMD and CBSD is the use of genetically resistant plants. Genetic resistance is a low cost method of controlling viruses that cause the two diseases. However, many countries lack CBSD resistant/tolerant cassava varieties. Recent studies have shown varying levels of CBSD tolerance. Elite 1,980 full-sib from 106 families from Nigeria evaluated in Uganda exhibited significant susceptibility to CBSD within two years of evaluation (Cu et al, 2021). Similarly, farmer preferred cultivars from Ghana and tested for response to mixed infection of CBSV and UCBSV showed susceptibility to the viruses (Elegba et al., 2020). Despite some of the setbacks, efforts have continued to look elsewhere for resistant genes including South America where ongoing work has shown resistance to CBSD in breeding lines DSC167 and DSC118 (Sheet et al., 2019). In the east and southern Africa, management efforts have focused on identification of superior clones to CBSD (Mukiibi et al., 2019) and introgressing the resistant genes in farmer preferred varieties (Munga, 2008). In Uganda, breeding efforts made for a period of 11 years have resulted in CBSD clones with reasonable resistance/ tolerance (Kawuki et al., 2016). As breeding is a long term activity, clones with resistant genes need to be distributed and evaluated in other countries that are experiencing the CBSD or threatened with the disease. Most of the countries affected by CBSD have reported CBSIs recognized strains, though more unknown strains could be circulating (Ndunguru et al., 2015). Introduced tolerant lines will need to be evaluated in hot spot areas given the ability of CBSV to quickly evolve (Alicai et al 2016).

Unlike the lack of availability of CBSD resistant varieties in many countries, there are several CMD resistant cassava varieties that have been developed (Houngue et al., 2019). The sources of resistance are CMD1 (polygenic recessive resistance), CMD2 (dominant monogenic type), and CMD3 which have been identified and introgressed from wild cassava to cassava cultivars (Akano et al., 2002;

Okogbenin et al., 2012; Fondong, 2017). To enhance CMD resistance in plants, CMD2 and CMD1 have been combined using genetic crosses (Fondong, 2017).

Transgenic cassava option

Improvement of resistance to CBSD and CMD, either through traditional breeding or genetic transformation, is challenging and time-consuming. Needless to say that the growth of transgenic cassava is limited by public opinion across Africa. The varying opinions has contributed to low adoption of potential varieties conferring novel resistance genes to CBSD and CMD. Scientists agree that increasing cassava productivity will require genetically transforming cassava with pest and disease tolerant/ resistant genes. However, they are also wary of consumerōs skepticism in light of limited understanding of GM technology (Adenle et al., 2012). Efforts to use transgenic approaches to CMD resistance has increased in recent years to overcome the limitations of conventional breeding (Vanderschuren et al., 2007; 2009). Typical targets for transgenic resistance include the viral non-coding intergenic region and messenger RNAs of rep-associated genes of CMGs, especially ACMV (Zhang et al., 2005; Fondong, 2017). In contrast to CMD as previously stated, limited natural resistance to CBSD has been identified and demonstrated. Because of this development, transgenic approaches are cardinal to reduce the impact of CBSD in Africa. However, host resistance has been identified for a few viruses only, and a limited number of commercial elite crop cultivars and rootstocks exhibit useful resistance. For example, in east Africa, 16 of 25 p500 transgenic lines showed foliar resistance to CBSD (Wagaba et al., 2017) compared to the non-transgenic cassava. Researchers in Uganda and Nigeria are conducting a limited number of trials to evaluate how the engineered cassava cultivars will perform in the field. If the materials prove superior over conventionally bred cultivars, farmers can adopt them. In Kenya work spanning several years has resulted in the approval of genetically modified cassava which confers resistance to CBSD for open cultivation (https;//alliancefor science.cornell.edu).

The deployment of virus-resistant transgenic plants has become an important strategy to implement effective and sustainable control measures against major viral diseases. Several transgenic plants with virus resistance have been demonstrated as an effective strategy against virus infections through the expression of coat protein genes, viral replicase genes, or other viral sequences. Transformation of resistant transgenic cassava (TMS60444) to CBSV has been achieved using RNAi technology by targeting a sequence of the CBSV coat protein (Yadav et al., 2011; Vanderschuren et al., 2012) and the gene demonstrated to be integrated within the genome. The mechanism of RNA mediated resistance involves RNA silencing, in which sequence-specific RNA degradation occurs (Kawazu et al., 2009). As the new molecular tools are developed, e.g. Clustered Regularly Interspaced Short Palindromic Repeats (CRISPRs) opportunities to develop CMD and CBSD resistance varieties will be enhanced.

Integrated Pest Management

Integrated pest management (IPM) is a strategy that encompasses all crop protection strategies involving biological, use of resistant varieties, cultural, physical, and chemical control practices. Although researchers agree that overall IPM programmes are required for the whole range of cassava pests and diseases, little progress has been made. This is in spite of likely significant effects on yield arising from CBSD, CMD, cassava bacterial blight, cassava anthracnose, cassava mealybug, and green mite. Recommendations for control of CBSD and CMD include the strict enforcement of quarantine procedures during exchange of cassava planting materials by the farmers. Cultural practices, especially the use of resistant or tolerant cultivars is cardinal and where necessary should be encouraged. In many countries of Africa were cassava seed system is mainly informal, use of virus-free planting material or clean planting material as often referred to should be encouraged.

Surveillance and diagnostics

Priority should be conducting regular surveillance in areas where there are no records of CBSD and CMD. Surveillance should be accompanied by carrying out a diagnosis of the samples collected from the surveys using standardized and harmonized protocols. Further, surveillance must be coordinated between countries and should have a reporting mechanism to ensure effective disease management. Establishing real-time centralized database is cardinal in sharing information on the occurrence of new virus strains and diseases. Surveillance especially for CBSD should also be implemented in cassava-growing regions of Africa not directly connected to the regions of the current distribution of the disease.

Given the difficulties associated with the recognition of symptoms of CMD and CBSD especially in varieties that do not show symptoms fully, laboratory diagnostic methods can play a critical role (Mbazibwa et al., 2009). Accurate virus diagnosis requires sensitive equipment and standardized procedures. Fortunately, appreciable investment in recent years in laboratory diagnostics have been made ranging from simple to more complex equipment. Polymerase chain reaction (PCR) and Real-time PCR are increasingly being used but the cost is prohibitive for many developing countries. Some low cost rapid test kits are required that can provide quick results in the field and can be valuable to scientists and extension agents. In Asia, an immunochromatographic strip test for detecting Sri Lankan cassava mosaic virus has been developed and can give a result within 15 minutes and does not require laboratory setting (https://www.nstda.or.th/en/news/news-years-2022). CBSD and CMD protocols are available for use by scientists across Africa for disease surveys and for detection (Sseruwagi et al., 2004, Shirima et al., 2017; Mbazibwa et al., 2009; Abarshi et al., 2010). The ultimate goal will be to document the new and old viruses by establishing a continental system of surveillance and monitoring.

Recently, mobile-based artificial intelligence (AI) tools for cassava pest and disease surveillance have been developed (Ramcharan et al., 2019). The tools perform several functions that include the following; real-time diagnosis (<1 min) - for presence of diseases or pests on cassava (CBSD, CMD and CGM). However, affordability and accessibility are the biggest challenges by the end users such as farmers, scientists and extension agents.

Stakeholder networks

Cassava stakeholders in Africa are faced with the gravity of CBSD and CMD and therefore a greatly strengthened and more effectively coordinated network is needed to manage the two diseases. Efforts are in place to tackle CBSD and CMD scourge, however, the efforts are not coordinated by key players such as donors, scientists, extension agents and non-governmental organizations with interest in cassava (Legg et al., 2014). Strengthening the linkages and interaction between Cassava stakeholders is paramount in addressing the impact of CBSD and CMD. The links between the stakeholders involved in cassava technology generation and dissemination, which are end products of cassava research are weak and sometimes inactive.

Conclusions

While cassava continues to be a crop of importance in Africa for reducing food security especially among rural households, there is need to address the issue of diseases so that the crop can be advocated as a contributor of poverty reduction. The expansion and economic impact of CBSD and CMD on yield requires specific disease management strategies and for continuous revision of these two important viral diseases. To curtail spread and reduce the impact of the two diseases, there is need to have coordinated efforts across the continent and integrate the management strategies. Particular efforts should be placed on quarantine measures since development and deployment of resistant CBSD, and CMD varieties are yet to be fully realized in most of the African countries affected by the two diseases.

Future directions

Going forward, future directions in tackling the two cassava viral diseases are highlighted:

- Conduct annual surveillance surveys including in high risk areas to ascertain extent of viruses causing CBSD and CMD and spread using standardized and harmonized protocols.
- Invest in rapid diagnostic capabilities in national research organisations to respond to threats posed by CBSD and CMD.
- Develop standardized and adapt robust protocols for detection of all species and strains of viruses causing CBSD and CMD.
- Characterize viruses to provide comprehensive data for disease management
- Establish regional phytosanitary networks in west, east, central and southern African countries
- Establish and strengthen breeding programmes for developing CBSD and CMD resistant and high yielding cultivars.
- Raise awareness amongst researchers, extension workers, plant protectionists, quarantine officers, farmers, and policymakers of cassava viruses and the threats they pose.
- Establish local and regional early warning systems for CBSD and CMD to facilitate rapid responses in case of new outbreaks.
- Encourage policy makers to participate in national and international conferences or symposiums on CBSD and CMD.

Author contributions

PC conceived the idea. PC and MT wrote the manuscript. PC designed the figures. All the authors contributed to the article and approved the submitted version.

Funding

This work is an output of the Zambia Skills Development and Entrepreneurship Project supported by the Citizen Economic Empowerment Commission through project number P-ZM-IEO-002 with funds provided by Africa Development Bank (AfDB).

Acknowledgement

The authors would like to thank Drs. James Legg and Peter Sseruwagi for insightful advice and comments.

Conflict of interest

There was no conflict of interest among the authors

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