Received: 13 September 2023 | Revised: 30 July 2024 | Accepted: 31 July 2024
DOI: 10.1002/fes3.573

Food and Energy Security WILEY

REVIEW

Cyanide in cassava: Understanding the drivers, impacts of climate variability, and strategies for food security

Jacinta Nyaika[1,2] | Louise Abayomi[1] | Aditya Parmar[1] | Onoriode Coast[3,4]

[1]Natural Resources Institute, University of Greenwich, Kent, UK
[2]Horticulture Department, Lilongwe University of Agriculture and Natural Resources, Lilongwe, Malawi
[3]School of Environmental and Rural Science, University of New England, Armidale, New South Wales, Australia
[4]Research School of Biology, The Australian National University, Canberra, Australian Capital Territory, Australia

Correspondence
Jacinta Nyaika, Natural Resources Institute, University of Greenwich, Central Avenue, Chatham Maritime, Kent ME4 4TB, UK.
Email: j.a.nyaika@greenwich.ac.uk

Abstract
The consumption of cassava, a vital staple food for more than 1 billion people worldwide, holds particular significance in sub-Saharan Africa (SSA). Expansion in cassava production in SSA is driven by increasing market demand, local consumption, and adaptability to diverse environments. However, cyanide concentration in cassava tubers and products across SSA ranges from 9 to 1148 ppm – most exceed the World Health Organisation's recommended safe level of 10 ppm. Such variation and high cyanide concentrations in cassava products are expected to be exacerbated by climate-induced increases in the frequency, intensity and occurrence of drought, heat waves and biotic stresses, further jeopardising regional food security. Thus, it is essential to examine cassava production and cyanide toxicity under climate change and their implications for food security in SSA. In this review, we look at the drivers of cassava production and spatial variation in cyanide concentrations across SSA, impacts of climate variability and biotic stresses on cassava cyanide concentrations in SSA, and crop management practices for reducing cyanogenic glucosides in cassava tubers. We surmise that urgent actions are required to adopt improved cassava varieties and management strategies that reduce cassava cyanide toxicity amid climate-induced challenges in SSA.

KEYWORDS
biotic stress, cassava, climate extremes, cyanide toxicity, food security, sub-Saharan Africa

1 | INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is widely grown in sub-Saharan Africa (SSA) and is a significant source of calories for about one billion people worldwide (FAOSTAT, 2023; Lambebo & Deme, 2022; Mbinda & Mukami, 2022). Cassava accounts for approximately two-thirds of SSA's population dietary intake (Rosenthal et al., 2012) and serves as an essential source of income for its farmers (Burns et al., 2010; Chetty et al., 2013; Mbanjo et al., 2021; Serdeczny et al., 2017). Cassava adapts well to various ecological and agronomic conditions, with substantial yields even in unfavourable environmental conditions, such as marginal soils, high temperatures, and droughts (Devi et al., 2022; Spencer & Ezidinma, 2017; Tabaglio et al., 2023). Models predict that cassava would thrive under conditions associated with climate extremes, including high temperatures, reduced soil moisture (i.e. short drought spells), and elevated atmospheric carbon dioxide (CO_2) (Brown et al., 2016; Forbes et al., 2020).

Cyanogenic glucosides are synthesised in cassava leaves during growth and are translocated and deposited in roots (Gleadow & Møller, 2014; Riis et al., 2003). Once the cassava roots are cut or bruised, the glucosides get hydrolysed by linamarase, leading to the production and release of the toxic hydrogen cyanide and acetone (Burns et al., 2010; Jørgensen et al., 2005). High hydrogen cyanide concentration in immature plants is exploited in some communities in SSA as insurance against social disruption and theft, as they are less likely stolen from farms prior to maturity (Alves, 2001; Gleadow et al., 2014; McMahon et al., 1995). Although cassava is a food security crop, high concentrations of cyanogenic glucosides and linamarin, and small amounts of lotaustralin and methyl linamarin, in its roots and leaves can make it unsafe for consumption (Cooke & De La Cruz, 1982; Gleadow & Møller, 2014).

Cassava cyanide poisoning is prevalent in communities that rely heavily on cassava as their primary source of sustenance (Alitubeera et al., 2019; Baguma, Nzabara, et al., 2021; Tshala-Katumbay et al., 2016), without adequate intake of sulphur in their diets (Kimani et al., 2013; Onabolu et al., 2001; Teles, 2002; Tor-Agbidye et al., 1999). Symptoms of cyanide poisoning and acute intoxication include dizziness, fatigue, headache, nausea, and diarrhoea (Burns et al., 2010; Kashala-Abotnes et al., 2018; Nhassico et al., 2008). These typically manifest within hours of consuming poorly processed cassava roots or leaves (Burns et al., 2010; Cumbana et al., 2007; Teles, 2002). Excessive cyanide consumption over a relatively short period coupled with a lack of protein diet can be disastrous and may lead to irreversible upper motor neuron damage, causing spastic paraparesis (known as Konzo) (Baguma et al., 2022; Cumbana et al., 2007; Siddiqi et al., 2020); Tropical Ataxic Neuropathy (TAN) (Cardoso et al., 2005; Lubulwa, 1999; Oluwole et al., 2000), a chronic neurological disorder; and (iii) hyperthyroidism, from the accumulation of thiocyanate (Opoku-Nkoom et al., 2013; Teles, 2002). Thiocyanate is a cyanide detoxification product that interferes with iodine metabolism.

Konzo epidemics are prevalent in many Southern, Central, and Eastern African areas and is worse during drought, conflict, and social upheaval (Cumbana et al., 2007; Kashala-Abotnes et al., 2018; Siddiqi et al., 2020). Tropical Ataxic Neuropathy (TAN) is common among older West African populations (Cardoso et al., 2005; Oluwole et al., 2000; Onabolu et al., 2001). High cyanide exposure can also aggravate ailments associated with iodine deficiency, such as goitre and cretinism (Bradbury et al., 2011; Bradbury & Denton, 2011, 2014; Cumbana et al., 2007; Teles, 2002).

The safety of cassava food products is often categorised into chemical, physical, and microbiological (Chiwona-Karltun et al., 2022). In this paper we focus on chemical safety. Specifically, the inherent cyanogenic glucosides in cassava roots and leaves. Here, we explore the use of traditional agronomic management practices to produce relatively safe cassava for consumption. The central question of this paper concerns itself with the potential of crop management practices in minimising the accumulation of cyanogenic glucosides in cassava tubers. To address this question, we focus on four points: (i) drivers of cassava production and spatial variation in cassava cyanide concentrations across SSA; (ii) the basis of cultivar selection and preferences for high cyanide content; (iii) climate-induced increases in abiotic and biotic stresses in SSA and their impacts on cassava cyanide concentrations; and (iv) traditional agronomic practices for reducing cyanogenic glucosides in cassava tubers. This research can inform interventions aimed at mitigating food safety challenges, and shape strategies for sustainable agriculture and policymaking in the region.

2 | DRIVERS OF PREFERENCE FOR CASSAVA PRODUCTION IN SSA

Cassava production has grown significantly in SSA, accounting for 61% of global production in 2020 (FAOSTAT, 2023; Mbanjo et al., 2021). The top three producers are Nigeria (59 t), the Democratic Republic of Congo (DRC, 40 t) and Ghana (22 t; Figure 1), whereas the highest yielding countries are Zambia (318 t ha^{-1}), Niger (283 t ha^{-1}), and Malawi (238 t ha^{-1}). The increase in cassava production in SSA is attributed to higher market demand, local consumption, and its adaptability to diverse ecological and agronomic systems (Abass et al., 2018; Awotide et al., 2014; Chimphepo et al., 2021). Furthermore, resilience of the cassava crop to physical damage in regions facing unrest has contributed to increased production (Burns et al., 2010; Chiwona-karltun et al., 2015; El-Sharkawy, 2004; Köcke, 2019; Shackelford et al., 2018). With Africa's population projected to triple by 2100 (United Nations Department of Economic and Social Affairs, 2022), the demand for cassava is expected to increase, making it a crucial food security crop for SSA (Parmar et al., 2017).

Most countries in the region took up cassava production as a famine-reserve crop during the most pressing times, such as droughts, locust attacks, and lean food season. High cassava production is also due to the crops ability to produce reasonable yields with limited inputs, and to be left in the field until harvest, which may span 12–24 months. In these situations, some farmers prefer cassava varieties with high cyanide content as this correlates with stress resistance, are less prone to predation by mammals, as well as require little to no management (Köcke, 2019; Mkumbira et al., 2003;

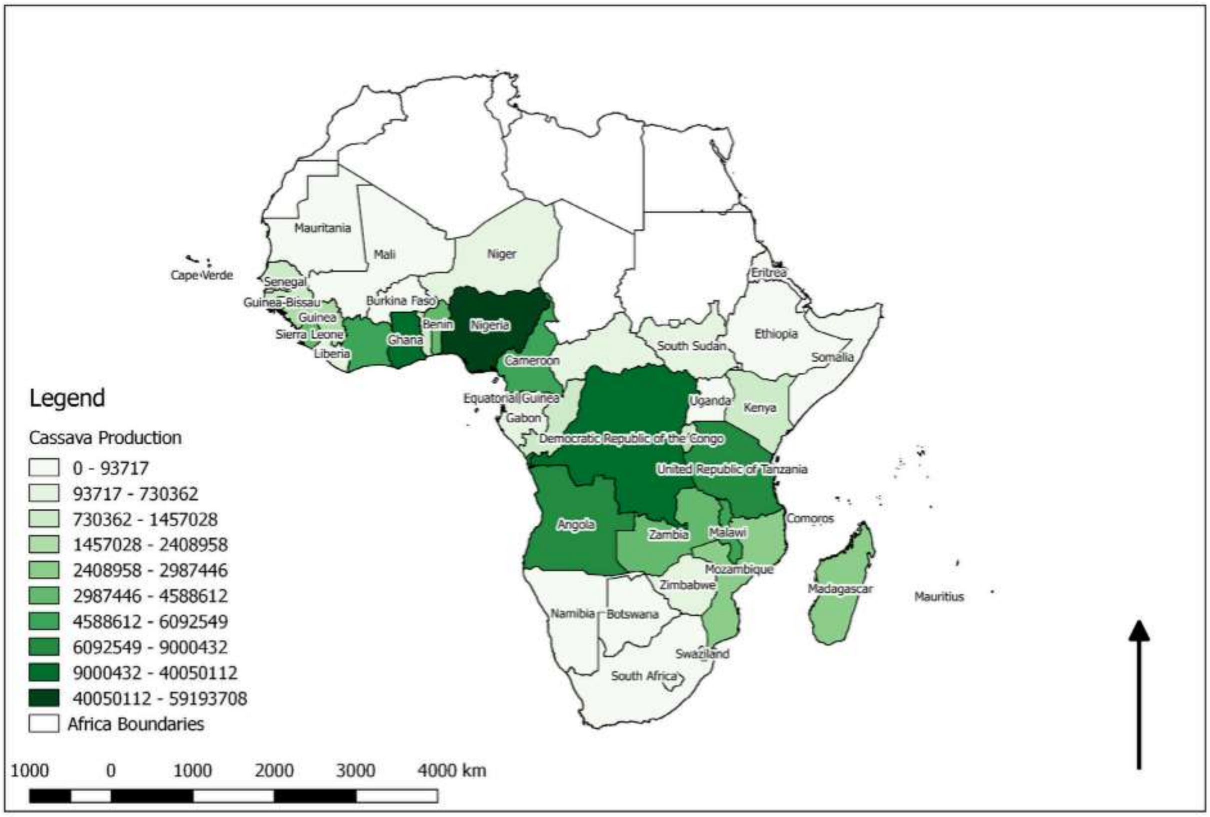

FIGURE 1 Production of cassava in sub-Saharan African (SSA) countries for the year 2020. The different shades of green denote the production quantities, dark green are the top producers whilst the lighter colour are the minimum producing countries. The data used to produce the plot is provided as supplementary information (Table S1). *Source*: (FAOSTAT, 2023).

Shackelford et al., 2018). The latter being critical during civil unrests (Burns et al., 2010; McKey et al., 2010; Nebiyu & Getachew, 2011).

Cassava breeders have been actively selecting for improved cassava varieties with low hydrogen cyanide, disease resistance, and high yields. However, the adoption of improved cassava varieties has been low (Table 1), with a few exceptions, such as Nigeria with a 73% adoption rate (Alene et al., 2015). The available information regarding the adoption of improved cassava varieties in most SSA countries is outdated, with the existing studies spanning well over a decade. Consequently, new research is urgently needed to assess the current adoption rates for these improved cassava varieties and their performance.

Patterns for adopting improved cassava varieties varies across SSA countries, and are influenced by farmers' preferences for specific traits, and differences in breeding objectives and programmes. For instance, in Nigeria, adoption of improved cassava varieties which were early maturing, and had low cyanide content was high, and were preferred to local types (Abass et al., 2018; Apu & Nwachukwu, 2011). By contrast, in Malawi, the adoption of improved varieties is low (Alene et al., 2013, 2015). Malawian farmers preferred the local types that had a high market value for their high dry matter, were early maturing and low in cyanide, even though they had low yields over improved varieties that were bitter (high cyanide) (Alene et al., 2013, 2015). Notwithstanding substantial investments in cassava research and development in SSA, farmers' access to improved cassava planting materials, fertilisers, and agrochemicals, are constrained by their high costs (Acheampong & Acheampong, 2020; Agwu & Anyaeche, 2007; Alene et al., 2013; Ojo & Ogunyemi, 2014; Osewe et al., 2021). On the other hand, limited awareness of the benefits and characteristics of select improved varieties further hinders adoption, alongside insufficient information dissemination, and extension services, being key factors (Abele et al., 2007; Wossen et al., 2019). Additionally, cassava's cultural significance and preference for locally adapted genotypes contribute to the reluctance to adopt introduced cultivars. The variability in agroecological zones and climate conditions in SSA poses challenges, as some improved cassava varieties may not be well-adapted or exhibit lower yields in different locations (Alene et al., 2015; Awotide et al., 2014). Furthermore, farmers hesitate to invest in new cultivars without market demand or profitability assurance (Acheampong et al., 2022; Apu & Nwachukwu, 2011; Tafesse et al., 2021). Addressing these issues will require a multifaceted approach. This will include improving

TABLE 1 Adoption of improved cassava varieties in some sub-Saharan Africa countries.

Country	Adoption (%) ICVs	Adoption (%) Local	Year	Cassava varieties	References
Angola	31.0	69.0	2009	Nghanarico, Maria cudianeca, Precole de Angola, Precole de Angola, Mundele Paco, TMS 4202 (Linda), MZ 96/0091, TMS 60142 (Perdiz), MZ 96/001323, TMS 40142, Manuela (Quizaquinha)	Alene et al. (2015)
Benin	66.0	34.0	2009	TMS30555, TMS30572 (30572/5), Ben 86062, RB 89509, Hombètè, Atinwéwé, Soukounon, Agbézi, Agblehoundo, Agric-rouge, Idilerou, Maboussa	Alene et al. (2015); Houngue et al. (2018); Sanoussi et al. (2015)
Burundi	29.0	71.0	2009	MM96/7204, MM96/0287, MM96/5280	Alene et al. (2015)
Cameroon	36.0 64.9 66.1	64.0 35.1 33.9	2009 2012 2019	TMS-92/0057, TMS-92/0326, TMS-96/1414, TMS-96/0023, M94/0121NR8085, NR88071-3, TMS-95/0109, NR880447-2, TMS-96/0102, M94/0121, TMS-96/1762	Alene et al. (2015); Chi et al. (2019); Njukwe and Kirscht (2013)
Côte d'Ivoire	20.0	80.0	2009	Yavo TME 7, TMS 4(2)1425 (IM93)	Alene et al. (2015)
Democratic Republic of Congo	48.0 28.8	50.0 72.2	2009 2019	Butamu (MV99/0395), Nsansi (9195/0160), RAV (85/297), MVUAMA 83/138, SADISA 91/203, Nambiyombiyo, M'baila, Nganga-na-butu, Nakarasai, M'Shediye, Nalubanda, Nabinzoza, Kanyunyi, Kamegere, Kabunga	Alene et al. (2015); Mubalama et al. (2019)
Ghana	36.0 47.0 41.2 25.0	64.0 53.0 59.8 75.0	2009 2012 2017 2020	Tek Bankye, Gblemoduade (TMS 50395), Afisiafi (TMS 30572), Bankye hemaa, Sika bankye, Deboo, Esi abaya	Acheampong et al. (2017); Alene et al. (2015); Kondo et al., 2020; Owusu and Emmanuel (2012)
Guinea	21.0	79.0	2009	TMS 30572	Alene et al. (2015)
Kenya	44.0 54.2	56.0 45.0	2009 2021	Serere, SS4, TMS 30572 (Migyera), TMs 30572, TM/14, MH93/OVA, kibandemeno, Tajirika (KME-08-02), Kaleso, Agriculture, KME 1	Alene et al. (2015); Osewe et al. (2021)
Malawi	29.0	61.3	2009	Mkondezi (MK91/478), Sauti (CH92/077), Manyokola	Alene et al. (2015)
Mozambique	19.0	81.0	2009	Chigona mafia, Nikwaha	Alene et al. (2015)
Nigeria	46.0 73.0	54.0 27.0	2009 2014	NR 8082 (Nicass 14), TMS 4(2)1425 (NC-Savanna, Nicass 2), TMS 30572 (NC Idi-Osle, Nicass 1), TMS 00/0203, TMS 0040, NR 01/0004, CR 41-10, TME 419, TMS 30572	Alene et al. (2015); Awotide et al. (2014); Ojo and Ogunyemi (2014); Opata et al. (2021); Wossen et al. (2017)

production and distribution mechanisms; enhancing affordability and accessibility of inputs; effective extension services for information dissemination; supportive policies and market linkages; and developing culturally and environmentally suitable varieties.

3 | SPATIAL VARIATION IN CASSAVA CYANIDE CONCENTRATIONS ACROSS SSA

Traditionally, cassava varieties have been classified as bitter or sweet based on their organoleptic properties (Chiwona-Karltun et al., 2004; Mkumbira et al., 2003; Pereira et al., 1981). While no consistent morphological characteristics are associated with cyanide concentration, typically, bitter varieties contain high (>100 ppm) levels of hydrogen cyanide, whereas sweet varieties contain low (<100 ppm) levels of hydrogen cyanide (Fukushima et al., 2016). However, at least one study includes a medium-level category for varieties with between 50 ppm and 100 ppm of hydrogen cyanide (Nambisan, 2011; Table 2). Alternative classifications based on cyanogenic glucoside content of 50–400 ppm for high cyanide and 15–50 ppm for low cyanide have also been proposed (Mbah et al., 2019;

TABLE 2 Classification of cassava varieties based on fresh root cyanide content.

Classification system	Description	Hydrogen cyanide concentration (ppm)	References
Ethnobotanical/ Organoleptic taste	Bitter Sweet/cool		Chiwona-Karltun et al. (2004, 2015); Dufour (1988); Mkumbira et al. (2003); Pereira et al. (1981)
	Bitter	>100	Fukushima et al. (2016)
	Sweet	<100	
Cyanogenic glucosides levels	Low	<100	Bokanga et al. (1994)
	High	>100	
	Low	<50	Nambisan (2011)
	Medium	50–100	
	High	>100	
	High	50–400	Chisenga (2021); Mbah et al. (2019); Ndubuisi and Chidiebere (2018)
	Low	15–50	
Toxicity	Innocuous/harmless	≤50	Bokanga et al. (1994); Brito et al. (2013); Ekanayake and Bokanga (1995)
	Moderately poisonous	50–100	
	Dangerously poisonous	100	
CODEX Alimentarius	CODEX STAN 238–2003 for sweet varieties	<50	Chiwona-Karltun et al. (2022)
	CODEX 300–2010 for Bitter varieties	>50	
World Health Organisation	Safe level for cassava products	10	Cardoso et al. (2005); Cumbana et al. (2007)

Ndubuisi & Chidiebere, 2018; Peprah et al., 2020). International organisations have set standards and guidelines for safe cyanide levels in cassava products. The World Health Organisation (WHO) has established a safe level of cyanogen in processed cassava products at 10 ppm (Cardoso et al., 2005; Cumbana et al., 2007; Nambisan, 2011; Ndubuisi & Chidiebere, 2018). Maximum limits for cyanide in end products may vary according to country or region. For example, in Indonesia, the limit is 40 ppm (Mota-Gutierrez & O'Brien, 2020; Quinn et al., 2022). The Codex Alimentarius Commission (Codex) has specific standards for sweet and bitter cassava, mandating that bitter cassava must be peeled and thoroughly cooked before consumption if the cyanide content exceeds 50 ppm on a fresh weight basis. Low cyanide or 'sweet' cassava, on the other hand, can be supplied fresh after appropriate preparation and packaging (Chiwona-Karltun et al., 2022).

Despite various classification systems and international standards, the farm-level assessment of cyanide content in cassava often relies on their ethnobotany and or organoleptic tests involving tasting of cassava roots. This approach is less sensitive, potentially unsafe, and subjective. Complex and expensive traditional laboratory techniques, and even the decentralised Bradbury cyanide kit, are typically inaccessible to farmers (Bokanga et al., 1994; Brito et al., 2013; Chiwona-karltun et al., 2015). Thus, there is a need for alternative testing methods that are accessible, easy to use, safe, reliable, low-cost, and can be used at the farm level (Chiwona-Karltun et al., 2004; Dufour, 1988; Pereira et al., 1981).

The concentration of cyanide in cassava roots varies across SSA (Figure 2). Despite efforts to mitigate cyanide levels, high amounts of cyanide in roots and leaves of cassava plants are still common in many SSA countries (Baguma, Malembaka, et al., 2021). For instance, in the Republic of Congo, cyanide concentrations in fresh cassava roots range from 414 to 1158 ppm (Kobawila et al., 2005), whereas in Mozambique, they range from 44 to 800 ppm (Cardoso et al., 2005; Cumbana et al., 2007; Ernesto et al., 2000). Similarly, in Côte d'Ivoire, cyanide concentrations vary from 9.1 to 498 ppm (Bakayoko et al., 2009; Heuberger, 2005). These levels exceed the thresholds the WHO set for safe consumption. The variations in hydrogen cyanide content within a country can be attributed to diverse factors. These include abiotic and biotic conditions during growth, agronomic management practices, and genotypic differences (Bokanga et al., 1994; Gleadow et al., 2016; Schmidt et al., 2018). Even in countries where some cassava cultivars reportedly exhibit low hydrogen cyanide content, such as in Tanzania (Imakumbili et al., 2020; Mtunguja et al., 2016; Mushumbusi, 2018)

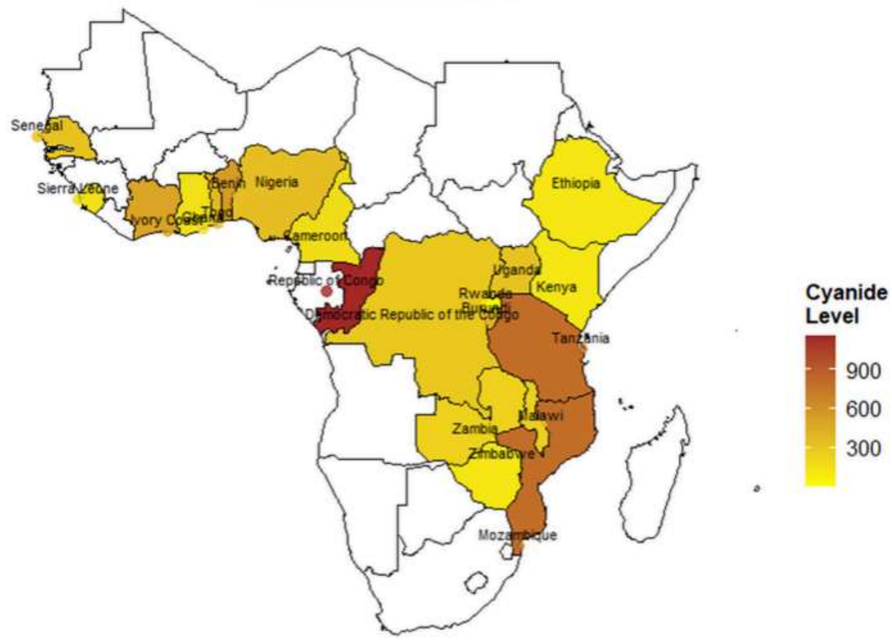

FIGURE 2 Reported maximum cyanide content (ppm) in cassava roots from Sub-Saharan Africa. Data and R script used to produce this plot are presented as supplementary information (Table S2; Script S1).

and Côte d'Ivoire (Bakayoko et al., 2009; Heuberger, 2005; Koko et al., 2014), there are still reports of alarmingly high concentrations of hydrogen cyanide in processed cassava products, surpassing the WHO safe limits by up to 50 times (Bakayoko et al., 2009; Heuberger, 2005; Imakumbili et al., 2020; Koko et al., 2014; Mtunguja et al., 2016; Mushumbusi, 2018). Consequently, farmers in these regions facing the challenge of selecting appropriate cultivars are constrained by their specific circumstances.

4 | CLIMATE VARIABILITY AND IMPACT ON CASSAVA CYANOGENESIS

The SSA region faces increased vulnerability to food insecurity due to climate change (Braimoh et al., 2019; Burns et al., 2010; Eze, 2018). Optimum cassava production requires an annual rainfall of between 600 to 1500 mm, temperature range of 25–32°C, and 12-h photoperiod for enhanced tuberisation (Sanoussi et al., 2015; Wassie, 2020). So far, three factors have been identified as potentially significant in cassava growth, cyanide accumulation and yield: rising temperatures, extreme droughts, and elevated atmospheric carbon dioxide (CO_2; Figure 3).

4.1 | Rising temperatures affect cassava cyanide

Extreme temperatures in SSA have become prevalent following intense temperature increases in inland subtropic areas (Ayanlade et al., 2022; Serdeczny et al., 2017). Global warming models show mean air temperature increases between 2070 and 2099 are forecast to be 2 to 5°C for SSA (Akinwumiju et al., 2020; Arneth et al., 2019; Serdeczny et al., 2017). Specifically, for the West, Central, and East Africa regions, temperature increases of 0.6, 1.1, and 2.1°C respectively are projected, whereas Southern Africa are expected to experience even higher temperatures of 1.2, 2.3, and 3.3°C for the projected 1.5, 2, and 3°C (Arneth et al., 2019).

Cultivating cassava under elevated temperatures has been the subject of several studies (Brown et al., 2016; Forbes et al., 2020) which have consistently shown a notable decrease in cyanide concentrations within the plant. This intriguing phenomenon has sparked scientific interest, and researchers propose that the underlying mechanism may be linked to changes in nitrogen allocation within the leaves (Brown et al., 2016; Forbes et al., 2020; Gleadow et al., 2009, 2016; Gleadow & Møller, 2014). It has been suggested that under high-temperature conditions, the photosynthetic capacity of cassava may experience a partial downregulation, leading to alterations in nitrogen allocation within the plant. In turn, these changes in nitrogen allocation may contribute to reduced cassava cyanide content (Gleadow et al., 2009; Gleadow & Møller, 2014).

4.2 | Effects of drought on cassava cyanide content

Projections for precipitation levels in Africa show variations in regional rainfall patterns (Bichet et al., 2020; Shongwe et al., 2011). Currently, some parts experience

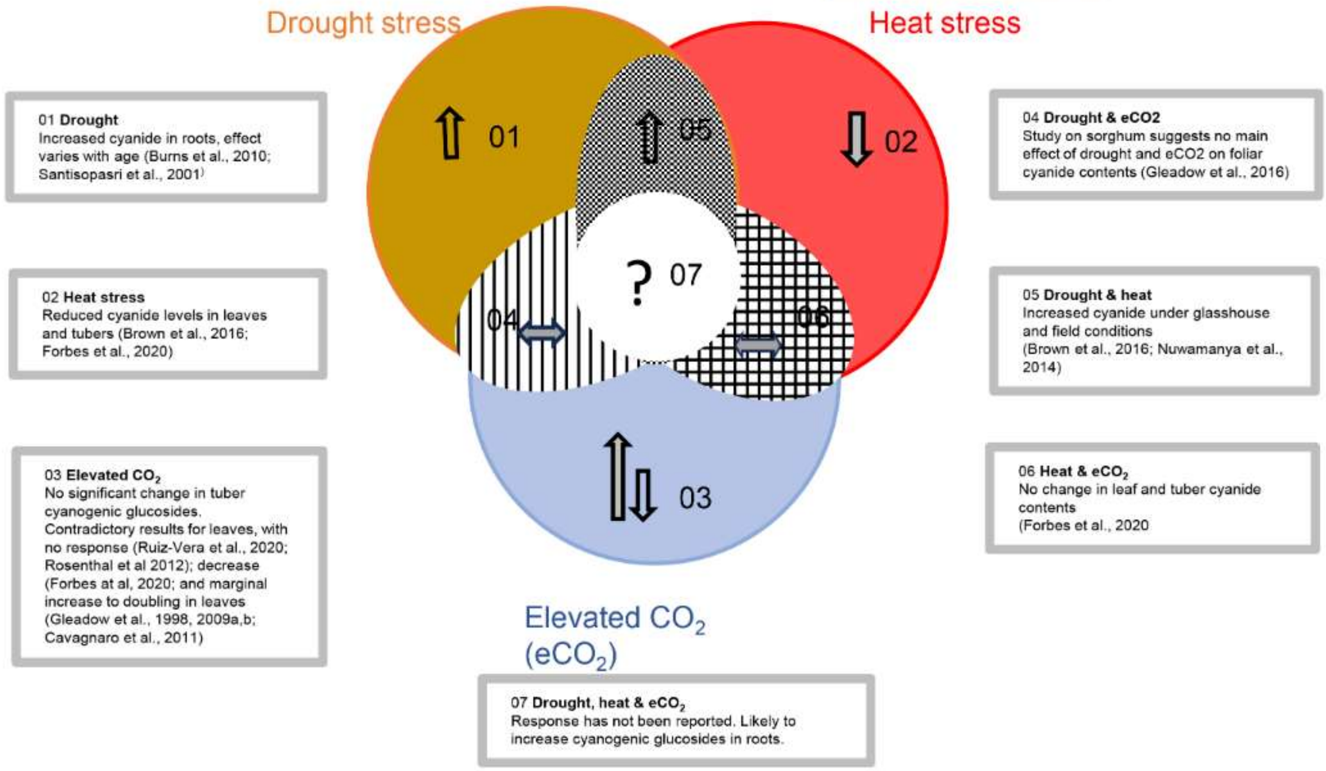

FIGURE 3 Influence of climate extremes on cassava cyanide concentration. References are in Table S3.

good rains while others have low rainfall. However, under a 1.5°C global warming scenario, Central, Eastern, and Southern Africa will experience decreased rainfall, whereas Western Africa will face increased monsoon rains (Arneth et al., 2019; Gudoshava et al., 2020; Serdeczny et al., 2017). At 2°C global warming, using the full Coupled Model Intercomparison Project Phase 5 (CMIP5) model, Sillmann et al. (2013) predicted the SSA region will experience more frequent drought spells and more dry months, ranging from 2 to 4 months (Arneth et al., 2019; Serdeczny et al., 2017; Trisos et al., 2022). The African region has had at least 341 drought events from the 1900s, compared with 168 drought events in America, 181 in Asia, 48 in Europe and 33 in Oceania (EM-DAT, 2023). Moreover, SSA had at least 233 drought events between 1980 to 2020 (EM-DAT, 2023; Nnopuechi, 2021), indicating that drought events have been recurring in the region, impacting millions of lives. Figure 4 shows that SSA countries including Angola, Mozambique, and Tanzania have each experienced more than seven drought events between 1980 and 2022. The recurring droughts in these countries stress the importance of cassava as both a staple and food security crop, especially when cereals fail, yet it is during the same drought period that cassava cyanide glucosides are high due to drought stress.

Drought stresses significantly increases cyanide content in cassava roots, with the effect varying depending on the growth stage of the plant (Adegbola, Abayomi, Adebowale, et al., 2018; Adegbola, Abayomi, Obadina, et al., 2018; Bokanga et al., 1994; Burns et al., 2010; Mtunguja et al., 2016; Santisopasri et al., 2001). Drought stress can disrupt normal plant metabolism, affecting the balance between cyanogenic glycoside production and detoxification enzymes in cassava (Bokanga et al., 1994; Gleadow et al., 2016; Vandegeer et al., 2013). As a result, drought-stressed cassava plants tend to exhibit higher cyanide content in their roots compared with plants grown under optimal water conditions. The magnitude of the effect may also depend on the duration and severity of the drought event (Adegbola, Abayomi, Adebowale, et al., 2018; Adegbola, Abayomi, Obadina, et al., 2018; Alves, 2001; Mtunguja et al., 2016; Vandegeer et al., 2013; Wasonga et al., 2020a).

4.3 | Effects of elevated atmospheric carbon dioxide (CO_2) on cassava safety

Elevated CO_2 levels alone can have varied effects on cassava's hydrogen cyanide content. Some studies have shown no significant change in leaf hydrogen cyanide content (Rosenthal et al., 2012; Ruiz-Vera et al., 2021); some others reported decreases (Forbes et al., 2020); and a few studies have shown marginal increases when CO_2

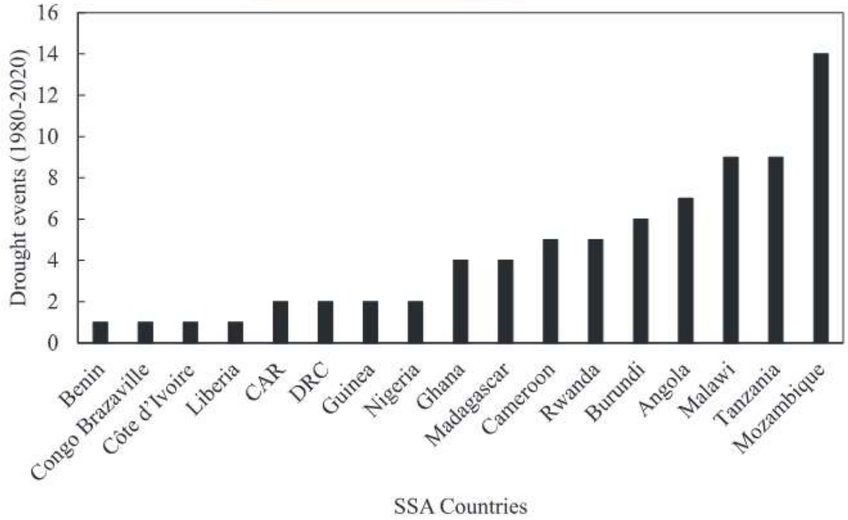

FIGURE 4 Occurrence of drought events in some SSA countries between 1980 and 2022. The data and references used to produce the plot are provided as supplementary information (Table S4). *Source*: EM-DAT, 2023.

levels were doubled (Cavagnaro et al., 2011; Gleadow et al., 1998, 2009). In contrast to studies on leaves, studies examining tuber cyanogenic glucoside levels, which contribute to hydrogen cyanide content, have generally shown no significant change in response to elevated CO_2 levels (Forbes et al., 2020). These findings suggest that the effect of elevated CO_2, if any, on tuber cyanogenic glucoside levels may differ from that observed in cassava leaves.

4.4 | Compound effects of extreme temperatures, droughts, and elevated carbon dioxide

Under climate change models, compound extremes resulting from the simultaneous occurrence of heat and drought are expected to increase (Lesk et al., 2022; Serdeczny et al., 2017). Studies have demonstrated that the interactive effects of heat and drought stress significantly elevate the toxicity levels of cyanide in cassava roots, both in controlled environments and field conditions (Brown et al., 2016; Nuwamanya et al., 2014; Figure 3). These findings suggest that with the projected increases in temperature and reduced precipitation in SSA, cassava may become more toxic for human consumption, necessitating additional energy and processes for detoxification to ensure its safety. Regarding the interaction of high temperatures and elevated CO_2 levels, no change in leaf cyanide content is observed, whilst higher concentrations are found in the tubers (Forbes et al., 2020). However, research is limited on the interactive effects of extreme drought and elevated CO_2 or the combined effects of drought, heat, and elevated CO_2 on cassava tuber cyanide (Figure 3). Nevertheless, such compound effects will likely further increase cyanogenic glucoside levels in cassava roots.

4.5 | Mechanisms of environmental stress in influencing cassava cyanogenic glucosides

Cyanogenic glucosides in cassava are produced as secondary metabolites during growth and transported to the tuber as part of resource allocation, serving various functions including nitrogen turnover (Forbes et al., 2020; Gleadow et al., 2009). High temperatures and drought stress disrupt the delicate balance of enzymatic processes involved in cyanogenic glucoside degradation (Brown et al., 2016; Zhao et al., 2015). This contributes to the build-up of cyanide in plant tissues (Brown et al., 2016; Vandegeer et al., 2013). Although high temperatures alone have been reported to reduce cyanides via association with photosynthetic down-regulation, which leads to changes in the distribution of nitrogen resources within the plant (McMahon et al., 2022; Ruiz-Vera et al., 2021). The altered resource allocation of photosynthates in stressed cassava plants, functions to enhance resilience to oxidative stress, ultimately resulting in higher cyanide concentrations in both leaves and roots (Gleadow et al., 2009, 2016; McKey et al., 2010).

5 | BIOTIC STRESS CAUSED BY INSECTS, PESTS, AND DISEASES HAD VARYING EFFECTS ON HYDROGEN CYANIDE LEVELS IN CASSAVA

Cyanide presence in cassava is generally thought to play a significant role in defence mechanisms against attacks from arthropod pests (Devi et al., 2022; Forbes et al., 2020; Ndubuisi & Chidiebere, 2018; Tivana et al., 2007). It is unclear whether cyanide also contributes to defence against disease attacks in cassava. In Table 3, we present literature

TABLE 3 Influence of insect/pests and disease attacks on cassava hydrogen cyanide content.

Pest/disease	Country	Change in hydrogen cyanide	Plant organ affected	References
Cassava whitefly (*Bamis tabacci*)	Germany	↑	Leaves	(Easson et al., 2021)
	Uganda	↑	Leaves	(Tumwesigye et al., 2006)
Burrowing bag (*Cyrtomenus bergi* hemiptera)	Colombia	↔	Root parenchyma	Riis et al. (2003)
Cassava Green Mite (*Mononychellus tanajoa*)	Kenya	↑	Leaves	Mutisya et al. (2013)
	Nigeria	↔	Leaves	Ezulike and Egwuatu (1992)
Variegated grasshopper (*Zonocerus variegatus* (L.))	Nigeria	↑	Leaves	Bernays et al. (1977)
Cassava Mosaic Disease (CMD)	Uganda	↑	Leaves/roots	Tumwesigye et al. (2006)
Cassava Brown Streak Disease (CBSD)	Uganda	↑	Roots	Nuwamanya et al. (2015)
Cassava Mosaic Disease (CMD)	Zaire (DRC)	↓	Leaves	Almazan and Theberge (1989)

that reports on the influence of insect pests and disease attacks on cassava cyanide content. Both laboratory (Easson et al., 2021) and field (Tumwesigye et al., 2006) studies undertaken in Germany and Uganda, respectively, showed that cassava whitefly attacks increase cyanide concentrations in cassava foliar parts. Conversely, Bernays et al. (1977) has linked higher hydrogen cyanide content to reduced infestation by the African variegated grasshopper on cassava leaves. Analysis of data reported by Mutisya et al. (2013) and Ezulike and Egwuatu (1992), indicate a non-linear relationship between cassava green mite infestation and cyanide content (Figure 5). Specifically, Mutisya et al. (2013) found that low cyanide content varieties ranging from 10 to 30 ppm were more prone to cassava green mite attack in Kenya. By contrast, high cyanide varieties in Nigeria experienced low cassava green mite infestation (Ezulike & Egwuatu, 1992). Cassava pests that attack the root parenchyma, such as the burrowing bug (*Cyrtomenus bergi*, Hemiptera), do not change cyanide glucoside concentrations in low cyanide varieties, and only show minimal changes in high cyanide varieties (Riis et al., 2003).

The most significant cassava diseases in SSA are Cassava Mosaic Disease (CMD), and Cassava Brown Streak Disease (CBSD). Both CMD and CBSD are caused by viral pathogens. Previous studies have demonstrated that the accumulation of total cyanogen in cassava leaves and roots increases with the severity of CMD infestation (Tumwesigye et al., 2006) and CBSD infestation (Nuwamanya et al., 2015) in cassava roots. Additionally, Almazan and Theberge (1989) findings support the same hypothesis severity of the disease significantly influences the response of the crop to increase or reduce cyanide content. Through their study where cassava leaves were attacked by CMD in Zaire (present Democratic Republic of Congo), cyanide content for cassava varieties that were resistant (*vars* TMS 50395 and TMS 30572) were lower than in the highly susceptible variety '*Isunikankiyan*'. Similarly, cassava varieties' tolerance levels to CBSD play a role in the concentration of cyanide content in diseased plants. For instance, Nuwamanya et al. (2015) found that the cassava varieties TME 14 and TME 204, known as high cyanogenic varieties with cyanide content of 106 ppm and 108 ppm, respectively, exhibited a percentage increase in cyanide content of 15% and 73% when affected by CBSD. On the other hand, the varieties 1/92/0067 and MM96/4271, known as low cyanogenic varieties with cyanide content of 23 ppm and 4 ppm, respectively, both experienced an increase in cyanide content of 99%when attacked by CBSD. However, all the three studies designs did not consider the existing knowledge regarding soil moisture content's influence on cassava cyanide build up, making it difficult for one to make a conclusion on the issue.

It is also worth noting that the transmission of CMD and CBSD is facilitated by arthropod pests such as aphids and whiteflies. Cassava whiteflies transmit CMD persistently and CBSD semi-persistently (Muhindo et al., 2020). Interestingly, cassava varieties resistant to CMD are susceptible to whitefly pests (Omongo et al., 2012). The influence of cyanide on defence mechanisms in cassava appears to be more pronounced against arthropod pests than diseases.

Interventions that aim at controlling insect pests and disease during production would be essential in reducing cyanogenic glucosides. Breeding for resistant varieties to pests and diseases has been one of the core objectives for cassava improvement in Africa for decades (Ceballos et al., 2004; Hahn et al., 1980; Sheat & Winter, 2023). Additionally, in various SSA countries, including Nigeria, Ghana, Uganda, and Tanzania, biological control agents have been introduced as part of Integrated Pest Management (IPM) strategies to

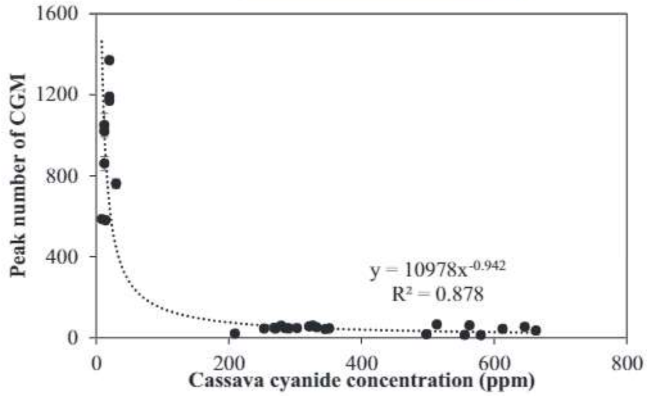

FIGURE 5 Peak number of cassava green mite (CGM) infestation in cassava varieties from Kenya and Nigeria. The data and references used to produce the plot are provided as supplementary information (Table S5). *Source*: Ezulike and Egwuatu (1992) and Mutisya et al. (2013).

combat pests in cassava production (Bellotti et al., 1999; Orek, 2024). These biological control programs aim to manage pests such as cassava mealybugs, green mites, and whiteflies. Natural enemies such as predatory mites, parasitic wasps, ladybugs, and lacewings have been introduced in cassava fields to regulate pest populations. The success of these biological control programs varies depending on factors such as the effectiveness of the introduced natural enemies, pest population dynamics, environmental conditions, and farmer adoption (Ratto et al., 2022). In many cases, biological control has proven effective in reducing pest populations and minimising damage to cassava crops, leading to improved yields and crop quality (Srinivasan et al., 2022). However, continued monitoring and adaptation to local conditions are essential to ensure the sustained success of these programs. By promoting environmentally friendly pest control practices and reducing reliance on chemical pesticides, these countries are working towards enhancing cassava productivity and the long-term sustainability of cassava farming systems.

6 | CROP MANAGEMENT INFLUENCES CYANIDE CONTENT IN CASSAVA TUBERS

The basal levels of cyanide in cassava tubers as well as its accumulation during a cropping cycle are influenced by a range of agronomic/crop management practices. These include irrigation and timing of planting, weeding and mulching practices, application of organic and inorganic fertiliser, and timing of harvest (see Table 4) (Adegbola, Abayomi, Adebowale, et al., 2018; Adegbola, Abayomi, Obadina, et al., 2018; Agbede, 2018; Alou et al., 2014; Biratu et al., 2022; Cadavid et al., 1998; Cuvaca et al., 2015; Hue et al., 2012; Hular-Bograd et al., 2011; Kyawt et al., 2020; Mtunguja et al., 2016; Nwokoro, 2021; Obigbesan, 1977; Omar et al., 2012; Saggafu et al., 2019; Santisopasri et al., 2001; Tchacondo et al., 2011; Wasonga et al., 2020b). Formulating effective strategies to reduce the accumulation of cyanide in cassava tubers will require better understanding of the influences of these practices. Farmers in SSA commonly utilise cassava cuttings as planting materials (Chikoti et al., 2019; Droppelmann et al., 2018; Osei et al., 2009). Cassava is sown by stem cuttings at the onset of the rainy season (Chikoti et al., 2019; Enesi et al., 2022). Selection of cultivars for stem cuttings are based on attributes such as taste of processed tubers (bitter or sweet), historical tuber yields, resistance to pests and diseases, and marketability. However, because cassava can withstand dry spells better than other staple crops such as maize and rice, it is often planted late in the rainy season, into low soil moisture (Enesi et al., 2022; Polthanee & Srisutham, 2017). Growing cassava in soils with low available water increases cyanide content in cassava (El-Sharkawy & Cadavid, 2002; Imakumbili et al., 2019a). A suite of crop management practices that can be used to manage cassava cyanide content are discussed below.

6.1 | Irrigation

Irrigation is a valuable tool to minimise cyanide content in cassava (Hular-Bograd et al., 2011). Adequate and consistent water supply offered by irrigation alleviates plant stress, and reduces accumulation of cyanogenic compounds, including cyanide (Forbes et al., 2020; Imakumbili et al., 2021; Vandegeer et al., 2013). Irrigation facilitates the dilution of the cyanides, which are water-soluble compounds, effectively lowering their concentration within the roots (Brown et al., 2016; Devi et al., 2022; Hular-Bograd et al., 2011; Vandegeer et al., 2013). In a rainfed field experiment, (Hular-Bograd et al., 2011) found that supplementing cassava with adequate water (60 mm per month) during the ninth month when there were no rains helped to reduce cyanide content in cassava roots, cv. 'Kasestart 50' by 40%. However, it is essential to note that the associated improvement in soil fertility and the promotion of uniform plant growth resulting from irrigation contribute to the mitigation of cyanide accumulation (Bokanga et al., 1994; Ekanayake & Bokanga, 1995).

6.2 | Weeds and mulches

Weeds inhibit growth and development of crops by increasing competition for essential resources including water, nutrients, and light (Fermont et al., 2009;

TABLE 4 Influence of agronomic practices on cassava cyanide content from selected countries.

Agronomic practice	Intervention	HCN[a] change	HCN[a] (ppm) treatment	HCN[a] (ppm) in control	Cultivar name	Tested part	Country	Reference
Irrigation	Supplementing with irrigation in the dry months (December–January)	↓	446.7	560.3	Kaserstat 50 (KU50)	Root	Thailand	Hular-Bograd et al. (2011)
	100% irrigation and K fertigation at 16 mM	↓	2.7	12.8	Mutura[b]	Root	Finland	Wasonga et al. (2020a)
	100% irrigation and K fertigation at 16 mM	↓	4.2	25.9	Mutura[b]	Leaves	Finland	Wasonga et al. (2020b)
Weeding	Weeding at 4 weeks interval for 6 months	↓	64.2–68.1	64.6–79.0	Kibandameno, Karembo, Nzalauka, Tajilika	Root	Kenya	Saggafu et al. (2019)
	Unweeded cassava plots	↑	1.12–3.99[c]	3.26–5.33[c]	NASE 0063, TME 14, Kirimumpale	Root	Uganda	Alou et al. (2014)
Mulching	Mulching with 1.2 kg/m^2 of *Panicum maximum*, Jacq. dry residues	↓	149–158	224–227	M Col 1505 'Verdecita'	Roots	Colombia	Cadavid et al. (1998)
Intercropping	NKP fertilisation in Intercropping cassava-maize system in a drought year	↓	2.4	2	TME 419	Roots	Nigeria	Nwokoro (2021)
Fertilisation	Use of vegetable waste and empty fruit bunches compost	↓	0.4–0.42	0.5	Pontan, Median	Root	Malaysia	Omar et al. (2012)
	Green manure (*Moringa oleifera* (Lam), *Leucaena leucocephala* (Lam.) and *Gliricidia sepium* (Jacq.) Kunth) application	↓	38.9–51.0	63.4–64.2	TMS 30572	Root	Nigeria	Agbede (2018)
	Chicken manure application	↔	14.64–15.21	14.28	Mweru	Root	Zambia	Biratu et al. (2022)
	N15-P15-K15- fertiliser application	↑	0.51	0.5	Pontan, Median	Roots	Malaysia	Omar et al. (2012)
	N15-P15-K15- fertiliser application	↓	50.4–56.0	63.4–64.2	TMS 30572	Roots	Nigeria	Agbede (2018)
	Different NPK fertiliser rates	↔	14.0–15.6	15.2	Mweru	Roots	Zambia	Biratu et al. (2022)
	Different NPK fertiliser rates	↔	46.0–95.2	76.3	Tapioca	Roots	Mozambique	Cuvaca et al. (2015)
	N application	↓	40	65	Red cassava	Roots	Japan	Kyawt et al. (2020)
		↔	56.8	76.3	Tapioca	Roots	Mozambique	Cuvaca et al. (2015)
	P-application	↔	46	76.3	Tapioca	Roots	Mozambique	Cuvaca et al. (2015)
	K application	↔	138–203	142.8–187.8	53101 (local)	Roots	Nigeria	Obigbesan (1977)
		↔	77–116	89.8–108.5	60506 & 60447 (Improved)			
		↓	4.2–10.5	8.0–25.9	Mutura[b]	Leaves	Finland	Wasonga et al. (2020)
		↓	2.7–5.6	3.7–12.8	Mutura[b]	Roots		
		↓	17.3–108.7	12–131.7	Salanga, Kalinda, Supa, Kiroba	Roots	Tanzania	
		↓	54	70	Red cassava	Roots	Japan	Kyawt et al. (2020)

(Continues)

TABLE 4 (Continued)

Agronomic practice	Intervention	HCN[a] change	HCN[a] (ppm) treatment	HCN[a] (ppm) in control	Cultivar name	Tested part	Country	Reference
Harvesting	Frequency of harvesting leaves-2-3 times	↑	171.6–322.5	105.6–173.6	K94, K98-7 & local	Leaves	Vietnam	Hue et al. (2012)
	Harvesting roots at 9 MAP[d]	↑	45.51–48.1	46.18–48.86	TMS98/0510 & TMS98/0505	Roots	Nigeria	Adegbola, Abayomi, Adebowale, et al. (2018); Adegbola, Abayomi, Obadina, et al. (2018)
		↓	560.3	616.2	Kaserstat 50 (KU50)	Root	Thailand	Hular-Bograd et al. (2011)
	Harvesting roots at 9 MAP[d]	↑	28–36	29.5–32	52101 & 60506	Roots	Nigeria	Obigbesan (1977)
	Harvesting roots at 12 MAP[d]	↓	17.63–21.14	46.18–48.86	TMS98/0510 & TMS98/0505	Roots	Nigeria	Adegbola, Abayomi, Adebowale, et al. (2018); Adegbola, Abayomi, Obadina, et al. (2018)
		↓	15–28	20–32	52101 and 60506	Roots	Nigeria	Obigbesan (1977)
		↓↑	21.8–51.1	22.3–38.2	R1, R5, R60, R90, KU 50, CMR 33-57-81	Roots	Thailand	Santisopasri et al. (2001)
		↑	873.8	616.2	Kaserstat 50 (KU50)	Root	Thailand	Hular-Bograd et al. (2011)
	Harvesting roots at 15 MAP[d]	↓↑	25–800	30–400	Kalolo, Kibandamemo, Kilusunga, Kiroba, Msenene, Nyamkagile	Roots	Tanzania	Mtunguja et al. (2016)
	Harvesting in wet season (April–May)	↓	93.05	n/a	96/1632-ITRA-TG	Roots	Togo	Tchacondo et al. (2011)
	Harvesting in dry season (December–January)	↑	375.3	n/a	96/1632-ITRA-TG			

[a]Hydrogen cyanide.
[b]Mutura is a Kenya variety that was studied in Finland.
[c]Denotes bitterness scale of 1–6, where 1 is for less bitter and 6 is highly bitter, and n/a is for not available in the paper.
[d]Months after planting.

Khanthavong, 2016; Pereira Soares et al., 2021). Weeds also act as vectors for pests and diseases which exacerbate biotic stresses on the cassava crop. The critical period for weed infestation that reduces cassava yield occurs within the first 2–3 months of crop establishment (Pereira Soares et al., 2021; Taylor et al., 2004). But it remains unclear whether the influence of weeds during this first 2–3 months is also critical for subsequent cyanide accumulation. Regular weeding has benefits for cassava production beyond enhancing growth and increasing access to resources as it reduces hydrogen cyanide content in tubers by 32% (Saggafu et al., 2019), and causes the tubers to be less bitter as demonstrated by (Alou et al., 2014) using organoleptic tests (Alou et al., 2014). Implementing proper weed control measures such as mulching and cover cropping can also minimise habitats for pest and disease vectors, disrupting their life cycles, and reducing their impact on cassava crops (Pereira Soares et al., 2021). Mulching also helps to retain soil moisture (Imakumbili et al., 2021) and suppress weed growth (Sangakkara et al., 2004), thereby reducing plant water stress. Mulches with low carbon-to-nitrogen (C:N) ratios can contribute nutrients to crop growth through rapid decomposition and nutrient recycling, improving soil structure, and lowering soil temperatures (Fasinmirin & Reichert, 2011). Mulching contributed to the reduction in root cyanide concentrations by around 30% (Cadavid et al., 1998), likely due to the negative correlation between cyanide content and water availability (Imakumbili et al., 2019a, 2021; see section 6.1 above). Despite these benefits, many farmers struggle with weed management due to its labour-intensive nature, competition for labour, and associated costs (Ekeleme et al., 2021). A short period of influence of weeds on cassava tuber cyanide content may present farmers with opportunities to allocate scarce resources to weed management and thus reduce tuber cyanide content. However, it is not unlikely that the period of influence may vary among weed species and even with cassava cultivars.

6.3 | Organic and inorganic fertilisers

Although fertilisation application improves cassava yields (Imakumbili, 2018; Okwu & Awurum, 2008; Wasonga et al., 2020b), it also influences cyanide content in cassava (Cadavid et al., 1998; Imakumbili, 2018). Organic fertilisers have varying effects on cassava cyanide content (Table 4). Reductions have been shown with vegetable waste (vermicompost and empty fruit bunch; Omar et al., 2012), and green manures such as moringa leaves at a rate of $5\,t\,ha^{-1}$ (Agbede, 2018), whereas chicken manure had negligible effects (Biratu et al., 2022). As with organic fertilisers, the effects of inorganic fertilisers on cassava cyanide content also varies (Table 4). High levels of potassium fertiliser reduced cyanide content in both cassava leaves and roots (El-Sharkawy & Cadavid, 2000; Imakumbili et al., 2019b; Kyawt et al., 2020; Wasonga et al., 2020a). Potassium is vital in translocating photosynthates from the leaves to the roots, contributing to the energy required to develop cassava storage organs (Imas & John, 2013). But the specific mechanisms by which potassium influences cyanide content in cassava roots is unknown. In contrast to potassium, nitrogen fertiliser application increases cyanide content, whereas phosphorus application does not appear to influence the cyanide levels in cassava leaves and roots. However, cassava roots grown in soils with high phosphorous content tend to exhibit higher cyanide contents, and the effects of mineral fertilisers on cyanide levels can be genotype-dependent (Ekanayake & Bokanga, 1995; Imakumbili et al., 2020).

The use of mineral fertilisers in SSA has declined over the past decade (Dimkpa et al., 2023; FAOSTAT, 2023), despite the introduction of government subsidies aimed at improving access for smallholder farmers (Ricker-Gilbert, 2020). A range of programs have been implemented to enhance agricultural productivity but theses have faced persistent challenges which have hindered their effectiveness (Baltzer & Hansen, 2011; Druilhe & Barreiro-Hurlé, 2012; Theriault & Smale, 2021). Smallholder farmers also face limitations in applying appropriate fertiliser amounts due to knowledge gaps. Logistical complexities in fertiliser delivery, which lead to delays, adversely affect fertiliser use efficiency (Bonilla-Cedrez et al., 2021; Dimkpa et al., 2023). Fertiliser subsidy programs prioritise cereal grain crops over root crops such as cassava. Furthermore, there is a prevailing notion among farmers that cassava can thrive with minimal inputs (Abass et al., 2014; Amelework et al., 2021) even though some cassava varieties require a considerable rate of application for the crop to produce optimal yields (Biratu et al., 2022; Chua et al., 2020; Ezui et al., 2016). This notion causes farmers to consider fertiliser application to cassava as a secondary option, except when it is grown within intercrop farming systems (Hauser et al., 2002).

6.4 | Intercropping

Intercropping is common in smallholder farms in SSA (Kuyper & Adjei-Nsiah, 2017; Parmar et al., 2017). Despite this prevalence, there is a shortage of information regarding the impact of intercropping on cassava in terms of reducing cyanide content in its roots. Nonetheless, we postulate that intercropping cassava has the potential to influence the cyanide content. The influence is likely contingent on factors such as companion plants or intercropping systems, nutrient competition, pest and disease management, soil health, and cultural practices used by farmers (Kuyper & Adjei-Nsiah, 2017; Nwokoro, 2021; Tang et al., 2020).

Nutrient competition is a prominent concern in cassava intercropping systems, as it can affect the availability of essential nutrients required for proper cyanide metabolism. For instance, in a cassava-maize intercropping system in Nigeria, Nwokoro (2021) observed that cassava root cyanide levels increased with the plant's age. Notably, unfertilised treatments did not accumulate more cyanide than fertilised treatments, highlighting the role of nutrient competition in cassava intercropping systems.

Pest and disease dynamics within cassava intercropping systems also have the potential to impact stress levels in cassava plants (Kuyper & Adjei-Nsiah, 2017) and consequently influence cyanide content. Reports suggest that intercropping cassava with cowpeas can reduce the egg populations of two whitefly species (*A. socialis* and *T. variabilis*) compared with monoculture cultivation. Remarkably, these effects have been observed to persist for up to 6 months after harvest (Bellotti et al., 1999; Riis et al., 2003). And as we discussed in section 5 above, whitefly infestations in cassava have been linked to increased cyanide levels (Easson et al., 2021; Tumwesigye et al., 2006). As such, intercropping may offer small-scale farmers an effective means of reducing pest populations and potentially mitigating cyanide content in cassava.

6.5 | Time of harvest

Cassava roots mature about 9–24 months after planting, whereas leaves are typically harvested around 4–5 months after planting (Hue et al., 2012; Sanusi et al., 2022; Wassie, 2020). The wide variation in time to harvest maturity of cassava tubers is due mostly to cultivar differences (i.e., genotypic variations). However, environmental conditions including temperature, water and nutrient availability, and the presence or absence of pests and diseases also influence the rate of development to maturity (Bokanga et al., 1994; Burns et al., 2010; Santisopasri et al., 2001). Tuber and leaf maturity are negatively correlated with leaf and tuber cyanide content (Adegbola, Abayomi, Adebowale, et al., 2018; Adegbola, Abayomi, Obadina, et al., 2018; Mtunguja et al., 2016). This relationship has been explored from various perspectives, including physiological, genetic, and environmental factors (Adegbola, Abayomi, Adebowale, et al., 2018; Adegbola, Abayomi, Obadina, et al., 2018; Cuvaca et al., 2015; Mtunguja et al., 2016; Santisopasri et al., 2001). Frequent harvesting of young leaves further increase hydrogen cyanide content in younger leaves of subsequent harvests (Hue et al., 2012). Like leaves, as tubers matures, the cyanide content reduces. A study of sweet cassava varieties (TMS/98/0510 and TMS/98/0505) showed 1.8%–4.6% reduction in cyanide content when the roots were harvested 9 months after planting and 3%–10% reduction at 12 months after planting (Adegbola, Abayomi, Adebowale, et al., 2018; Adegbola, Abayomi, Obadina, et al., 2018). These findings highlight the importance of timing of harvest on tuber cyanide content. Harvests at tuber maturity would ensure reduced cyanide content. But waiting until tuber maturity may not always be possible in food insecure communities.

7 | CONCLUSION AND RECOMMENDATIONS

This paper highlights the urgent concern of changing patterns of cyanogenesis in cassava, a staple crop in SSA. Despite increased production and research efforts, cassava varieties with high cyanide concentrations continue to be cultivated, increasing the risk of exceeding post-processing limits recommended by WHO/FAO. The region faces additional challenges due to climate variability – extreme and/or prolonged drought and heat spells, and increased pests and diseases, exacerbating cyanide accumulation and posing health risks to consumers. Consequently, previously classified 'sweet' cassava varieties may no longer be categorised as such due to these factors.

To address this issue and ensure safe and nutritious cassava consumption, we recommend screening of cassava varieties. Breeding programs which recognise trade-offs for desired traits, that is, low hydrogen cyanide potential, increased resistance to pests and diseases, high yields, alongside consumer preferences are required. There is also a need to unravel molecular pathways responsible for the interactions between climate stresses, cassava physiology, and cyanogenic glycoside metabolism, which will aid in developing targeted mitigation strategies. Additionally, comprehensive interaction studies are also needed to understand better the complex interactions between extreme droughts, heat, elevated CO_2 levels, and cyanogenic glycoside metabolism.

Furthermore, farm management strategies are also deemed effective in reducing cyanide glucosides in cassava during the production cycle. For instance, discouraging late planting and promoting the selection of cassava varieties with low cyanide levels and adjusted planting timing to avoid prolonged dry spells are vital steps to mitigate cyanide toxicity. Implementing agronomic practices such as irrigation, weeding, mulching, fertiliser application, and pests and disease management can reduce cassava's cyanide concentrations. Nevertheless, smallholder farmers are less likely to use them in their cassava fields because the crop is believed to be hardy (Tabaglio et al., 2023) and produces yields, even with little effort. Some of these practices (e.g. irrigation and fertilisation) would increase production costs, rendering it expensive for farmers to produce significant economic yields (Ricker-Gilbert, 2020). Therefore, alternative practices better suited to smallholder farmers in SSA are needed. A potential option for sustainable production of safe cassava in SSA would be using agroecology practices (Shackelford et al., 2018). Agroecological practices offer a promising solution to mitigate biotic stress in cassava production caused by insects/pests, diseases, and abiotic stressors (McKey et al., 2010). Cassava production in agro-ecological set up promotes biodiversity, enhancing soil health, and fostering ecological balance, creates a resilient agroecosystem that can effectively suppress pest and disease outbreaks and reduce the production of cyanogenic glucosides in cassava (Delaquis et al., 2017; McKey et al., 2010; Shackelford et al., 2018). Implementing crop rotation, intercropping, and polyculture can help disrupt the pest and disease cycle while conserving natural predators and biological control agents (Bellotti et al., 1999; Kuyper & Adjei-Nsiah, 2017), which would be affordable to African smallholder farmers. Agroecological practices also emphasise good field hygiene, sanitation, and regular crop monitoring, enabling early detection and timely intervention.

SSA governments should invest and lead strategies, plans, and policies that support knowledge exchange and skills development on sustainable agronomic practices and technologies to reduce cyanide toxicity in cassava. By facilitating research, reducing land access pressures and supporting extension services, SSA governments can contribute significantly to efforts aimed at ensuring food security and the well-being of its population. SSA governments should also galvanise public health measures to reduce the risks of consuming cassava products with high cyanide. The measures could range from educating farmers and consumers about the dangers of consuming cassava with high cyanide content, to providing access to rapid, semi-quantitative, colorimetric test kits to farmers and local communities which they can easily use to determine the cyanogenic potential of their cassava products.

AUTHOR CONTRIBUTIONS

Jacinta Nyaika, Louise Abayomi and Onoriode Coast conceived the idea for the manuscript. Jacinta Nyaika performed the literature search and data collation and wrote the initial draft with support from Louise Abayomi and Onoriode Coast. All authors read, reviewed, and approved the final manuscript.

ACKNOWLEDGMENTS

We thank the Commonwealth Scholarship Commission for the PhD scholarship, enabling JN to undertake this research at the University of Greenwich, Natural Resources Institute, and the Lilongwe University of Agriculture and Natural Resources (LUANAR) for granting JN study leave. OC received support from Research England's 'Expanding Excellence in England' (E3)-funded Food and Nutrition Security Initiative of the Natural Resources Institute, University of Greenwich. OC acknowledges and recognises the Nganyaywana (Anaiwan) people as the traditional owners and custodians of the land on which he works and lives, and he pays respect to their Elders past and present. Dr Lucie Büchie is thanked for their generous contributions to earlier drafts.

CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Jacinta Nyaika https://orcid.org/0000-0003-0175-9871
Louise Abayomi https://orcid.org/0000-0003-0479-1463
Aditya Parmar https://orcid.org/0000-0002-2662-1900
Onoriode Coast https://orcid.org/0000-0002-5013-4715

REFERENCES

Abass, A. B., Awoyale, W., Alenkhe, B., Malu, N., Asiru, B. W., Manyong, V., & Sanginga, N. (2018). Can food technology innovation change the status of a food security crop? A review of cassava transformation into "bread" in Africa. *Food Reviews International*, *34*(1), 87–102. https://doi.org/10.1080/87559129.2016.1239207

Abass, A. B., Towo, E., Mukuka, I., Ranaivoson, R., Tarawali, G., & Kanju, E. (2014). *Growing cassava: A training manual from production to postharvest*. International Institute of Tropical Agriculture.

Abele, S., Twine, E., Ntawuruhunga, P., Baguma, Y., Kanobe, C., & Bua, A. (2007). *Adoption of improved cassava varieties in Uganda: Implications for agricultural research and technology dissemination*. African Association of Agricultural Economists Conference, 1–17 https://hdl.handle.net/10568/91428

Acheampong, P. P., & Acheampong, L. D. (2020). Analysis of adoption of improved cassava (Manihot esculenta) varieties in Ghana: Implications for agricultural technology disseminations. *International Journal of Food and Agricultural Economics*, *8*(3), 233–246. https://ageconsearch.umn.edu/record/305326/?ln=en

Acheampong, P. P., Addison, M., & Wongnaa, C. A. (2022). Assessment of impact of adoption of improved cassava varieties on yields in Ghana: An endogenous switching approach. *Cogent Economics and Finance*, *10*(1), 2008587. https://doi.org/10.1080/23322039.2021.2008587

Acheampong, P. P., Nimo-wiredu, A., Amengor, N. E., Haleegoah, J., Adu-appiah, A., & Asante, B. O. (2017). Root and tuber crops technologies adoption and impact study in Ghana: The case of improved cassava technologies.

Adegbola, O., Abayomi, L., Obadina, A., Adebowale, A., Adegunwa, M., & Sanni, L. (2018). Effect of variety, age at maturity, and drying method on physicochemical properties of high quality cassava flour (HQCF). *Food Chain*, *7*(2), 100–111. https://doi.org/10.3362/2046-1887.00012

Adegbola, O. O., Abayomi, L. A., Adebowale, A. A., Sanni, L. O., Adegunwa, M., & Obadina, A. O. (2018). *Assessing the influence of climate change on cassava cyanogenesis and mycotoxin formations*. Federal University of Agriculture, Abeokuta, Ogun State. Nigeria. www.cassavagmarkets.nri.org

Agbede, T. (2018). Effect of green manure application on cassava (Manihot esculenta Crantz) growth, yield quantity and quality in degraded alfisols. *Pertanika Journal of Tropical Agricultural Science*, *41*(4), 1757–1777. http://www.pertanika.upm.edu.my

Agwu, A. E., & Anyaeche, C. L. (2007). Adoption of improved cassava varieties in six rural communities in Anambra State, Nigeria. *African Journal of Biotechnology*, *6*(2), 89–98. https://www.ajol.info/index.php/ajb/article/view/56105

Akinwumiju, A. S., Adelodun, A. A., & Orimoogunje, O. I. (2020). Agro-Climato-edaphic zonation of Nigeria for a cassava cultivar using GIS-based analysis of data from 1961 to 2017. *Scientific Reports*, *10*(1), 1–15. https://doi.org/10.1038/s41598-020-58280-4

Alene, A. D., Abdoulaye, T., Rusike, J., Manyong, V., & Walker, T. S. (2015). The effective of crop improvement programmes from the perspectives of varietal output and adoption: Cassava, cowpea, soybean and yam in sub-Saharan Africa and maize in west and Central Africa. In T. S. Walker & J. Alwanga (Eds.), *Crop improvement, adoption, and impact of improved varieties in food crops in sub-Saharan Africa* (1st ed., pp. 388–405). CABI. https://doi.org/10.1079/9781780644011.0000

Alene, A. D., Khataza, R., Resources, N., Chibwana, C., Ntawuruhunga, P., & Moyo, C. (2013). Economic impacts of cassava research and extension in Malawi and Zambia. *Journal of Development and Agricultural Economics*, *5*(11), 457–469. https://doi.org/10.5897/jdae2013.0496

Alitubeera, P. H., Eyu, P., Kwesiga, B., Ario, A. R., & Zhu, B.-P. (2019). Outbreak of cyanide poisoning caused by consumption of cassava Flour-Kasese District, Uganda, September 2017. *Morbidity and Mortality Weekly Report*, *68*(13), 308–311. https://doi.org/10.15585/mmwr.mm6813a3

Almazan, A. M., & Theberge, R. L. (1989). Influence of cassava mosaic virus on cassava leaf-vegetable quality. *Tropical Agriculture*, *66*(4), 305–308. https://journals.sta.uwi.edu/ojs/index.php/ta/article/view/1885

Alou, I. N., Mudde, B., Musinguzi, J., William, O., Hafashimana, D. L., Kanzikwera, R. C., & Mwebaze, M. (2014). Inherent soil fertility and weed pressure explain tuber bitterness of improved cassava varieties on farms in Uganda. *Scholarly Journal of Agricultural Science*, *47*, 420–426. http://www.scholarly-journals.com/SJAS

Alves, A. A. C. (2001). *Cassava botany and physiology* (pp. 67–89). Biology, Production and Utilization. https://doi.org/10.1079/9780851995243.0067

Amelework, A. B., Bairu, M. W., Maema, O., Venter, S. L., & Laing, M. (2021). Adoption and promotion of resilient crops for climate risk mitigation and import substitution: A case analysis of cassava for south African agriculture. *Frontiers in Sustainable Food Systems*, *5*(April), 1–14. https://doi.org/10.3389/fsufs.2021.617783

Apu, U., & Nwachukwu, I. (2011). Effect of adoption of improved cassava varieties on farmers' income in Abia state, Nigeria. *Journal of Agriculture and Social Research (JASR)*, *11*(2), 138–155. https://www.ajol.info/index.php/jasr/article/view/78640

Arneth, A., Denton, F., Agus, F., Elbehri, A., Erb, K., Osman Elasha, B., Rahimi, M., Rounsevell, M., Spence, A., & Valentin, R. (2019). Framing and context. In J. M. P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, & K. Kissick (Eds.), *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (1st ed., pp. 77–129). IPCC. https://doi.org/10.1017/9781009157988.003

Awotide, B., Abdoulaye, T., Alene, A., & Manyong, V. (2014). Assessing the extent and determinants of adoption of improved cassava varieties in south-western Nigeria. *Journal of Development and Agricultural Economics*, *6*(9), 376–385. https://doi.org/10.5897/jdae2014.0559

Ayanlade, A., Oluwaranti, A., Ayanlade, O. S., Borderon, M., Sterly, H., Sakdapolrak, P., Jegede, M. O., Weldemariam, L. F., & Ayinde, A. F. O. (2022). Extreme climate events in sub-Saharan Africa: A call for improving agricultural technology transfer to enhance adaptive capacity. *Climate Services*, *27*(June), 100311. https://doi.org/10.1016/j.cliser.2022.100311

Baguma, M., Malembaka, E. B., Bahizire, E., Mudumbi, G. Z., Shamamba, D. B., Matabaro, A. N., Rigo, J. M., Njamnshi, A. K., & Chabwine, J. N. (2021). Revisiting konzo risk factors in three areas differently affected by spastic paraparesis in eastern Democratic Republic of the Congo discloses a prominent role of the nutritional status—A comparative cross-sectional study. *Nutrients*, *13*(8), 2628. https://doi.org/10.3390/nu13082628

Baguma, M., Migabo, C., Nzabara, F., Sami, W. L., Akili, C. M., Lwamushi, S. M., Bisimwa, J. M., Nkemba, A., Chirhalwirwa, P., Maheshe, G. B., Rigo, J. M., & Chabwine, J. N. (2022). Impact of seasonal variation and processing methods on the cassava-derived dietary cyanide poisoning, nutritional status, and Konzo appearance in south-Kivu, eastern D.R. Congo. *Processes*, *10*(2), 337–355. https://doi.org/10.3390/pr10020337

Baguma, M., Nzabara, F., Maheshe Balemba, G., Malembaka, E. B., Migabo, C., Mudumbi, G., Bito, V., Cliff, J., Rigo, J. M., & Chabwine, J. N. (2021). Konzo risk factors, determinants and etiopathogenesis: What is new? A systematic review. *NeuroToxicology*, *85*(February), 54–67. https://doi.org/10.1016/j.neuro.2021.05.001

Bakayoko, S., Soro, D., Nindjin, C., Dao, D., Tschannen, A., Girardin, O., & Assa, A. (2009). Evaluation of cyanogenic potential and organoleptic properties in cassava (Manihot esculenta Crantz.) roots of improved varieties in Côte D'ivoire.

African Journal of Food Science, *3*(11), 328–333. http://www.academicjournals.org/ajfs

Baltzer, K. T., & Hansen, H. (2011). *Agriculture input subsidies in sub-Saharan Africa*.

Bellotti, A. C., Smith, L., & Lapointe, S. L. (1999). Recent advances in cassava pest management. *Annual Review of Entomology*, *44*, 343–370. https://doi.org/10.1146/annurev.ento.44.1.343

Bernays, E. A., Chapman, R. F., Leather, E. M., McCaffery, A. R., & Modder, W. W. D. (1977). The relationship of *Zonocerus variegatus* (L.) (Acridoidea: Pyrgomorphidae) with cassava (*Manihot esculenta*). *Bulletin of Entomological Research*, *67*(3), 391–404. https://doi.org/10.1017/S0007485300011202

Bichet, A., Diedhiou, A., Hingray, B., Evin, G., Touré, N. E., Browne, K. N. A., & Kouadio, K. (2020). Assessing uncertainties in the regional projections of precipitation in CORDEX-AFRICA. *Climate Change*, *162*, 583–601. https://doi.org/10.1007/s10584-020-02833-z

Biratu, G. K., Elias, E., & Ntawuruhunga, P. (2022). Does the application of mineral and organic fertiliser affect cassava tuber quality? An evidence from Zambia. *Journal of Agriculture and Food Research*, *9*(March), 100339. https://doi.org/10.1016/j.jafr.2022.100339

Bokanga, M., Ekanayake, I. J., Dixon, A., & Porto, M. (1994). Genotype-environment interactions for cyanogenic potential in cassava. *Acta Horticulturae*, *375*, 131–140. https://doi.org/10.17660/actahortic.1994.375.11

Bonilla-Cedrez, C., Chamberlin, J., & Hijmans, R. J. (2021). Fertilizer and grain prices constrain food production in sub-Saharan Africa. *Nature Food*, *2*(10), 766–772. https://doi.org/10.1038/s43016-021-00370-1

Bradbury, J. H., Cliff, J., & Denton, I. C. (2011). Uptake of wetting method in Africa to reduce cyanide poisoning and konzo from cassava. *Food and Chemical Toxicology*, *49*(3), 539–542. https://doi.org/10.1016/j.fct.2010.04.049

Bradbury, J. H., & Denton, I. C. (2011). Mild methods of processing cassava leaves to remove cyanogens and conserve key nutrients. *Food Chemistry*, *127*(4), 1755–1759. https://doi.org/10.1016/j.foodchem.2011.02.053

Bradbury, J. H., & Denton, I. C. (2014). Mild method for removal of cyanogens from cassava leaves with retention of vitamins and protein. *Food Chemistry*, *158*, 417–420. https://doi.org/10.1016/j.foodchem.2014.02.132

Braimoh, A., Elizabeth Buck, L., Fraval, S., Etten, van, J., Hammond, J., Bogard, J. R., Ng, M., van Etten, J., Herrero, M., Oosting, S. J., de Boer, M. I. J., Lannerstad, M., Teufel, N., Lamanna, C., Rosenstock, T. S., Pagella, T., Vanlauwe, B., Dontsop-Nguezet, P. M., Baines, D., … van Wijk, M. T. (2019). Food access deficiencies in sub-saharan Africa: Prevalence and implications for agricultural interventions. *Frontiers in Sustainable Food Systems*, *3*(5), 104. https://doi.org/10.3389/fsufs.2019.00104

Brito, V., Rabacow, A., & Cereda, M. (2013). Classification of nine month old cassava cultivars by cyanide levels. *Geneconserve*, *12*(47), 35–49. http://www.geneconserve.pro.br/site/articles/lib/pastaup/Geneconserve%5B2013%5D.pdf

Brown, A. L., Cavagnaro, T. R., Gleadow, R., & Miller, R. E. (2016). Interactive effects of temperature and drought on cassava growth and toxicity: Implications for food security? *Global Change Biology*, *22*(10), 3461–3473. https://doi.org/10.1111/gcb.13380

Burns, A., Gleadow, R., Cliff, J., Zacarias, A., & Cavagnaro, T. (2010). Cassava: The drought, war and famine crop in a changing world. *Sustainability*, *2*(11), 3572–3607. https://doi.org/10.3390/su2113572

Cadavid, L. F., El-Sharkawy, M. A., Acosta, A., & Sánchez, T. (1998). Long-term effects of mulch, fertilization and tillage on cassava grown in sandy soils in northern Colombia. *Field Crops Research*, *57*(1), 45–56. https://doi.org/10.1016/S0378-4290(97)00114-7

Cardoso, A. P., Mirione, E., Ernesto, M., Massaza, F., Cliff, J., Rezaul Haque, M., & Bradbury, J. H. (2005). Processing of cassava roots to remove cyanogens. *Journal of Food Composition and Analysis*, *18*(5), 451–460. https://doi.org/10.1016/j.jfca.2004.04.002

Cavagnaro, T. R., Gleadow, R. M., & Miller, R. E. (2011). Plant nutrient acquisition and utilisation in a high carbon dioxide world. *Functional Plant Biology*, *38*(2), 87–96. https://doi.org/10.1071/FP10124

Ceballos, H., Iglesias, C. A., Pérez, J. C., & Dixon, A. G. O. (2004). Cassava breeding: Opportunities and challenges. *Plant Molecular Biology*, *56*(4), 503–516. https://doi.org/10.1007/s11103-004-5010-5

Chetty, C. C., Rossin, C. B., Gruissem, W., Vanderschuren, H., & Rey, M. E. C. (2013). Empowering biotechnology in southern Africa: Establishment of a robust transformation platform for the production of transgenic industry-preferred cassava. *New Biotechnology*, *30*(2), 136–143. https://doi.org/10.1016/j.nbt.2012.04.006

Chi, Z. T., Mformi, M. I., & Wouapi, H. A. N. (2019). Adoption and impact of improved cassava (Manihot esculenta Crantz) production technology on farmers welfare in Mezam division of the north west region of Cameroon. *International Journal of Innovation and Scientific Research*, *46*(1), 60–73. http://www.ijisr.issr-journals.org/

Chikoti, P. C., Mulenga, R. M., Tembo, M., & Sseruwagi, P. (2019). Cassava mosaic disease: A review of a threat to cassava production in Zambia. *Journal of Plant Pathology*, *101*(3), 467–477. https://doi.org/10.1007/s42161-019-00255-0

Chimphepo, L., Alamu, E. O., Monjerezi, M., Ntawuruhunga, P., & Saka, J. D. K. (2021). Physicochemical parameters and functional properties of flours from advanced genotypes and improved cassava varieties for industrial applications. *Food Science and Technology*, *147*, 111592. https://doi.org/10.1016/j.lwt.2021.111592

Chisenga, S. M. (2021). Primary quality control parameters of cassava raw materials. In *Cassava – Biology, production, and use*. IntechOpen. https://doi.org/10.5772/intechopen.97879

Chiwona-Karltun, L., Brimer, L., & Jackson, J. (2022). Improving safety of cassava products. In *Root, tuber and banana food system innovations* (pp. 241–258). Springer Nature. https://doi.org/10.1007/978-3-030-92022-7_8

Chiwona-Karltun, L., Brimer, L., Saka, J. D. K., Mhone, A. R., Mkumbira, J., Johansson, L., Bokanga, M., Mahungu, N. M., & Rosling, H. (2004). Bitter taste in cassava roots correlates with cyanogenic glucoside levels. *Journal of the Science of Food and Agriculture*, *84*(6), 581–590. https://doi.org/10.1002/jsfa.1699

Chiwona-Karltun, L., Nyirenda, D., Mwansa, C. N., Kongor, J. E., Brimer, L., Haggblade, S., & Afoakwa, E. O. (2015). Farmer preference, utilization, and biochemical composition of improved cassava (*Manihot esculenta* Crantz) varieties in Southeastern Africa. *Economic Botany*, *69*(1), 42–56. https://www.jstor.org/stable/24825460

Chua, M. F., Youbee, L., Oudthachit, S., Khanthavong, P., Veneklaas, E. J., & Malik, A. I. (2020). Potassium fertilisation is required to sustain cassava yield and soil fertility. *Agronomy*, *10*(8), 1103. https://doi.org/10.3390/agronomy10081103

Cooke, R. D., & De La Cruz, E. M. (1982). The changes in cyanide content of cassava (Manihot esculenta crantz) tissue during plant development. *Science of Food and Agriculture*, *33*(3), 269–275. https://doi.org/10.1002/jsfa.2740330312

Cumbana, A., Mirione, E., Cliff, J., & Bradbury, J. H. (2007). Reduction of cyanide content of cassava flour in Mozambique by the wetting method. *Food Chemistry*, *101*(3), 894–897. https://doi.org/10.1016/j.foodchem.2006.02.062

Cuvaca, I. B., Eash, N. S., Zivanovic, S., Lambert, D. M., Walker, F., & Rustrick, B. (2015). Cassava (*Manihot esculenta* Crantz) tuber quality as measured by starch and cyanide (HCN) affected by nitrogen, phosphorus, and potassium fertilizer rates. *Journal of Agricultural Science*, *7*(6), 36–49. https://doi.org/10.5539/jas.v7n6p36

Delaquis, E., De Hann, S., & Wyckhuys, K. A. (2017). On-farm diversity offsets environmental pressures in tropical agroecosystems: A synthetic review for cassava-based systems. *Agriculture, Ecosystems and Environment*, *251*, 226–235. https://doi.org/10.1016/j.agree.2017.09.037

Devi, B., Kumar, M. N., Chutia, M., & Bhattacharyya, N. (2022). Abiotic and biotic stress challenges of cassava in changing climate and strategies to overcome: A review. *Scientia Horticulturae*, *305*(111432), 1–15. https://doi.org/10.1016/j.scienta.2022.111432

Dimkpa, C., Adzawla, W., Pandey, R., Atakora, W. K., Kouame, A. K., Jemo, M., & Bindraban, P. S. (2023). Fertilisers for food and nutrition security in sub-Saharan Africa: An overview of soil health implications. *Frontiers in Soil Science*, *3*, 1123931. https://doi.org/10.3389/fsoil.2023.1123931

Droppelmann, K., Günther, P., Kamm, F., Rippke, U., Voigt, C., & Walenda, B. (2018). *Cassava, the 21 st century crop for smallholders?* https://doi.org/10.18452/19137

Druilhe, Z., & Barreiro-Hurlé, J. (2012). Feritiliser subsidies in sub-Saharan Africa (No. 12; 04).

Dufour, D. L. (1988). Cyanide content of cassava (*Manihot esculenta*, Euphorbiaceae) cultivars used by Tukanoan Indians in Northwest Amazonia. *Economic Botany*, *42*(2), 255–266. https://doi.org/10.1007/BF02858929

Easson, M. L. A. E., Malka, O., Paetz, C., Hojná, A., Reichelt, M., Stein, B., van Brunschot, S., Feldmesser, E., Campbell, L., Colvin, J., Winter, S., Morin, S., Gershenzon, J., & Vassão, D. G. (2021). Activation and detoxification of cassava cyanogenic glucosides by the whitefly *Bemisia tabaci*. *Scientific Reports*, *11*(1), 1–14. https://doi.org/10.1038/s41598-021-92553-w

Ekanayake, I. J., & Bokanga, M. (1995). A review of production agronomy and cyanogenesis. *2nd International Scientific Meeting of the Cassava Biotechnology network, Bogor (Indonesia)*, *1*, 548–556. https://cgspace.cgiar.org/handle/10568/56432

Ekeleme, F., Dixon, A., Atser, G., Hauser, S., Chikoye, D., Korie, S., Olojede, A., Agada, M., & Olorunmaiye, P. M. (2021). Increasing cassava root yield on farmers' fields in Nigeria through appropriate weed management. *Crop Protection*, *150*(May 2020), 105810. https://doi.org/10.1016/j.cropro.2021.105810

El-Sharkawy, M. A. (2004). Cassava biology and physiology. *Plant Molecular Biology*, *56*, 481–501. https://doi.org/10.1007/s11103-005-2270-7

El-Sharkawy, M. A., & Cadavid, L. F. (2000). Genetic variation within cassava germplasm in response to potassium. *Experimental Agriculture*, *36*(3), 323–334. https://doi.org/10.1017/S0014479700003045

El-Sharkawy, M. A., & Cadavid, L. F. (2002). Response of cassava to prolonged water stress imposed at different stages of growth. *Experimental Agriculture*, *38*(3), 333–350. https://doi.org/10.1017/S001447970200306X

EM-DAT. (2023). *The international disaster database*. Centre for Research on the Epidemiology of Disasters-CRED. http://www.emdat.be/database

Enesi, R. O., Hauser, S., Pypers, P., Kreye, C., Tariku, M., & Six, J. (2022). Understanding changes in cassava root dry matter yield by different planting dates, crop ages at harvest, fertiliser application and varieties. *European Journal of Agronomy*, *133*, 126448. https://doi.org/10.1016/j.eja.2021.126448

Ernesto, M., Cardoso-, A. P., Cli, J., & Bradbury, J. H. (2000). Cyanogens in cassava flour and roots and urinary thiocyanate concentration in Mozambique. *Journal of Food Composition and Analysis*, *13*, 1–12. http://www.idealibrary.com

Eze, J. N. (2018). Drought occurrences and its implications on the households in Yobe state, Nigeria. *Geoenvironmental Disasters*, *5*(18), 1–10. https://doi.org/10.1186/s40677-018-0111-7

Ezui, K. S., Franke, A. C., Mando, A., Ahiabor, B. D. K., Tetteh, F. M., Sogbedji, J., Janssen, B. H., & Giller, K. E. (2016). Fertiliser requirements for balanced nutrition of cassava across eight locations in West Africa. *Field Crops Research*, *185*, 69–78. https://doi.org/10.1016/j.fcr.2015.10.005

Ezulike, T. O., & Egwuatu, R. I. (1992). Resistance of cassava cultivars to green spider mite, (*Mononychellus tanajoa* dar) infestation in Nigeria. *Nigerian Journal of Entomology*, *12*, 61–69. http://esnjournal.com.ng/download/Vol_12/vol_12g7.pdf

FAOSTAT. (2023). *FAOSTAT*. Food Balance Sheet. https://www.fao.org/statistics/en/

Fasinmirin, J. T., & Reichert, J. M. (2011). Conservation tillage for cassava (*Manihot esculenta* crantz) production in the tropics. *Soil and Tillage Research*, *113*(1), 1–10. https://doi.org/10.1016/j.still.2011.01.008

Fermont, A., van Asten, P., Tittonell, P., van Wijk, M., & Giller, K. (2009). Closing the cassava yield gap: An analysis from smallholder farms in East Africa. *Field Crops Research*, *112*(1), 24–36. https://doi.org/10.1016/j.fcr.2009.01.009

Forbes, S. J., Cernusak, L. A., Northfield, T. D., Gleadow, R. M., Lambert, S., & Cheesman, A. W. (2020). Elevated temperature and carbon dioxide alter resource allocation to growth, storage and defence in cassava (*Manihot esculenta*). *Environmental and Experimental Botany*, *173*(January), 103997. https://doi.org/10.1016/j.envexpbot.2020.103997

Fukushima, A. R., Nicoletti, M. A., Rodrigues, A. J., Pressutti, C., Almeida, J., Brandão, T., Kinue Ito, R., Bafille Leoni, L. A., Spinosa, S., & De, H. (2016). Cassava flour: Quantification of cyanide content. *Food and Nutrition Sciences*, *7*(7), 592–599. https://doi.org/10.4236/fns.2016.77060

Gleadow, R., Pegg, A., & Blomstedt, C. K. (2016). Resilience of cassava (*Manihot esculenta* Crantz) to salinity: Implications for food security in low-lying regions. *Journal of Experimental Botany*, *67*(18), 5403–5413. https://doi.org/10.1093/jxb/erw302

Gleadow, R. M., Evans, J. R., Mccaffery, S., & Cavagnaro, T. R. (2009). Growth and nutritive value of cassava (*Manihot esculenta* Cranz.)

are reduced when grown in elevated CO2. *Plant Biology*, *11*, 76–82. https://doi.org/10.1111/j.1438-8677.2009.00238.x

Gleadow, R. M., Foley, W. J., & Woodrow, I. E. (1998). Enhanced CO2 alters the relationship between photosynthesis and defence in cyanogenic Eucalyptus cladocalyx *F. Muell*. *Plant, Cell and Environment*, *21*(1), 12–22. https://doi.org/10.1046/j.1365-3040.1998.00258.x

Gleadow, R. M., & Møller, B. L. (2014). Cyanogenic glycosides: Synthesis, physiology, and phenotypic plasticity. *Annual Review of Plant Biology*, *65*, 155–185. https://doi.org/10.1146/annurev-arplant-050213-040027

Gudoshava, M., Misiani, H. O., Segele, Z. T., Jain, S., Ouma, J. O., Otieno, G., Anyah, R., Indasi, V. S., Endris, H. S., Osima, S., Lennard, C., Zaroug, M., Mwangi, E., Nimusiima, A., Kondowe, A., Ogwang, B., Artan, G., & Atheru, Z. (2020). Projected effects of 1.5°C and 2°C global warming levels on the intra-seasonal rainfall characteristics over the greater horn of Africa. *Environmental Research Letters*, *15*(3), 34037. https://doi.org/10.1088/1748-9326/ab6b33

Hahn, S. K., Terry, E. R., & Leuschner, K. (1980). Breeding cassava for resistance to cassava mosaic disease. *Euphytica*, *29*, 673–683. https://doi.org/10.1007/BF00023215

Hauser, S., Wairegi, L., Asadu, C. L. A., Asawalam, D. O., Jokthan, G., & Ugbe, U. (2002). Cassava system cropping guide. In *Cassava: Biology, production and utilization* (Vol. *19*). CABI. https://cgspace.cgiar.org/handle/10568/82528

Heuberger, C. (2005). *Cyanide content of cassava and fermented products with focus on attiéké and attiéké garba*. Swiss Federal Institute of Technology Zurich. https://doi.org/10.3929/ethz-a-005182128

Houngue, J. A., Pita, J. S., Cacaï, G. H. T., Zandjanakou-Tachin, M., Abidjo, E. A. E., & Ahanhanzo, C. (2018). Survey of farmers' knowledge of cassava mosaic disease and their preferences for cassava cultivars in three agro-ecological zones in Benin. *Journal of Ethnobiology and Ethnomedicine*, *14*(1), 29. https://doi.org/10.1186/s13002-018-0228-5

Hue, K. T., Van, D. T. T., Ledin, I., Wredle, E., & Spörndly, E. (2012). Effect of harvesting frequency, variety and leaf maturity on nutrient composition, hydrogen cyanide content and cassava foliage yield. *Asian-Australasian Journal of Animal Sciences*, *25*(12), 1691–1700. https://doi.org/10.5713/ajas.2012.12052

Hular-Bograd, J., Sarobol, E., Rojanaridpiched, C., & Sriroth, K. (2011). Effect of supplemental irrigation on reducing cyanide content of cassava variety Kasetsart 50. *Kasetsart Journal (Natural Science)*, *45*(6), 985–994. https://li01.tci-thaijo.org/index.php/anres/article/view/245286

Imakumbili, M. L. E. (2018). Influence of nitrogen, phosphorus and potassium on cyanogenic glucoside production in cassava grown in some soils of Mtwara region, Tanzania. In Sokoine University of Agriculture (Vol. *53*). https://www.suaire.sua.ac.tz/handle/123456789/2158

Imakumbili, M. L. E., Semu, E., Semoka, J. M. R., Abass, A., & Mkamilo, G. (2019a). Cyanogenic glucoside production in cassava: The comparable influences of varieties, soil moisture content and nutrient supply. *BioRxiv*, 649236. https://doi.org/10.1101/649236

Imakumbili, M. L. E., Semu, E., Semoka, J. M. R., Abass, A., & Mkamilo, G. (2019b). Soil nutrient adequacy for optimal cassava growth, implications on cyanogenic glucoside production: A case of konzo-affected Mtwara region, Tanzania. *PLoS One*, *14*(5), e0216708. https://doi.org/10.1371/journal.pone.0216708

Imakumbili, M. L. E., Semu, E., Semoka, J. M. R., Abass, A., & Mkamilo, G. (2020). Plant tissue analysis as a tool for predicting fertiliser needs for low cyanogenic glucoside levels in cassava roots: An assessment of its possible use. *PLoS One*, *15*(2), e0228641. https://doi.org/10.1371/journal.pone.0228641

Imakumbili, M. L. E., Semu, E., Semoka, J. M. R., Abass, A., & Mkamilo, G. (2021). Managing cassava growth on nutrient poor soils under different water stress conditions. *Heliyon*, *7*(6), e07331. https://doi.org/10.1016/j.heliyon.2021.e07331

Imas, P., & John, K. (2013). *Potassium nutrition of cassava*. E-Ifc, 34. https://www.ipipotash.org/publications/eifc-284

Jørgensen, K., Bak, S., Busk, P. K., Sørensen, C., Olsen, C. E., Puonti-Kaerlas, J., & Møller, B. L. (2005). Cassava plants with a depleted cyanogenic glucoside content in leaves and tubers. Distribution of cyanogenic glucosides, their site of synthesis and transport, and blockage of the biosynthesis by RNA interference technology. *Plant Physiology*, *139*(1), 363–374. https://doi.org/10.1104/pp.105.065904

Kashala-Abotnes, E., Sombo, M. T., Okitundu, D. L., Kunyu, M., Makila-Mabe, G. B., Tylleskär, T., Sikorskii, A., Banea, J. P., Ngoyi, D. M., Tshala-Katumbay, D., & Boivin, M. J. (2018). Dietary cyanogen exposure and early child neurodevelopment: An observational study from the Democratic Republic of Congo. *PLoS One*, *13*(4), e0193261. https://doi.org/10.1371/journal.pone.0193261

Khanthavong, P. (2016). Effect of weed biomass on cassava yield related to weeding times. *Advances in Plants & Agriculture Research*, *5*(5), 5–8. https://doi.org/10.15406/apar.2016.05.00194

Kimani, S., Moterroso, V., Lasarev, M., Kipruto, S., Bukachi, F., Maitai, C., David, L., & Tshala-Katumbay, D. (2013). Carbamoylation correlates of cyanate neuropathy and cyanide poisoning: Relevance to the biomarkers of cassava cyanogenesis and motor system toxicity. *Springerplus*, *2*(1), 1–8. https://doi.org/10.1186/2193-1801-2-647

Kobawila, S. C., Louembe, D., Keleke, S., Hounhouigan, J., & Gamba, C. (2005). Reduction of the cyanide content during fermentation of cassava roots and leaves to produce bikedi and ntoba mbodi, two food products from Congo. *African Journal of Biotechnology*, *4*(7), 689–696. https://doi.org/10.5897/ajb2005.000-3128

Köcke, S. (2019). *The perception of cassava in Malawi* [Uppsala University, Sweden]. https://uu.diva-portal.org/smash/get/diva2:1384180/FULLTEXT01.pdf

Koko, C. A., Kouame, B. K., Anvoh, B. Y., Amani, G. N., & Assidjo, E. N. (2014). Comparative study on physicochemical characteristics of cassava roots from three local cultivars in Côte D'ivoire. *European Scientific Journal*, *10*(33), 418–432.

Kondo, K., Cacho, O., Fleming, E., Villano, R. A., & Asante, B. O. (2020). Dissemination strategies and the adoption of improved agricultural technologies: The case of improved cassava varieties in Ghana. *Technology in Society*, *63*(September), 101408. https://doi.org/10.1016/j.techsoc.2020.101408

Kuyper, T. W., & Adjei-Nsiah, S. (2017). *Intercropping and crop rotations in cassava cultivation: A production systems approach* (pp. 355–374). Burleigh Dodds Science Publishing Limited. https://doi.org/10.19103/as.2016.0014.26

Kyawt, Y. Y., Lukkananukool, A., Htwe, W. M., & Aung, M. (2020). Effect of different fertilization rates on cyanogen and foliage and tuber yields of cassava. *Agricultural Sciences*, *2*(1), 304. https://doi.org/10.30560/as.v2n1p304

Lambebo, T., & Deme, T. (2022). Evaluation of nutritional potential and effect of processing on improving nutrient content of cassava (*Manhot esculenta* Crantz) roots and leaves. *BioRxiv*, 1–39. https://doi.org/10.1101/2022.02.04.479097

Lesk, C., Anderson, W., Rigden, A., Coast, O., Jägermeyr, J., McDermid, S., Davis, K. F., & Konar, M. (2022). Compound heat and moisture extreme impacts on global crop yields under climate change. *Nature Reviews Earth and Environment*, *3*(12), 872–889. https://doi.org/10.1038/s43017-022-00368-8

Lubulwa, G. (1999). An ex post economic evaluation of a project to reduce the hydrogen cyanide potential in cassava cultivars in Africa. *Impact Assessment and Project Appraisal*, *17*(3), 183–192. https://doi.org/10.3152/147154699781767783

Mbah, E. U., Nwankwo, B. C., Njoku, D. N., & Gore, M. A. (2019). Genotypic evaluation of twenty-eight high- and low-cyanide cassava in low-land tropics, southeast Nigeria. *Heliyon*, *5*(6), e01855. https://doi.org/10.1016/j.heliyon.2019.e01855

Mbanjo, E. G. N., Rabbi, I. Y., Ferguson, M. E., Kayondo, S. I., Eng, N. H., Tripathi, L., Kulakow, P., & Egesi, C. (2021). Technological innovations for improving cassava production in sub-Saharan Africa. *Frontiers in Genetics*, *11*(January), 1–21. https://doi.org/10.3389/fgene.2020.623736

Mbinda, W., & Mukami, A. (2022). Breeding for postharvest physiological deterioration in cassava: Problems and strategies. *CABI Agriculture and Bioscience*, *3*(1), 1–18. https://doi.org/10.1186/s43170-022-00097-4

McKey, D., Cavagnaro, T. R., Cliff, J., & Gleadow, R. (2010). Chemical ecology in coupled human and natural systems: People, manioc, multitrophic interactions and global change. *Chemoecology*, *20*(2), 109–133. https://doi.org/10.1007/s00049-010-0047-1

McMahon, J., Sayre, R., & Zidenga, T. (2022). Cyanogenesis in cassava and its molecular manipulation for crop improvement. *Journal of Experimental Botany*, *73*(7), 1853–1867. https://doi.org/10.1093/jxb/erab545

McMahon, J. M., White, W. L., & Sayre, R. T. (1995). Cyanogenesis in cassava (*Manihot esculenta* Crantz). *Journal of Experimental Botany*, *46*(288), 731–741. https://www.jstor.org/stable/23694927

Mkumbira, J., Chiwona-Karltun, L., Lagercrantz, U., Mahungu, N. M., Saka, J., Mhone, A., Bokanga, M., Brimer, L., Gullberg, U., & Rosling, H. (2003). Classification of cassava into "bitter" and "cool" in Malawi: From farmers' perception to characterisation by molecular markers. *Euphytica*, *132*(1), 7–22. https://doi.org/10.1023/A:1024619327587

Mota-Gutierrez, J., & O'Brien, G. M. (2020). Cassava consumption and the occurrence of cyanide in cassava in Vietnam. *Indonesia and Philippines. Public Health Nutrition*, *23*(13), 2410–2423. https://doi.org/10.1017/S136898001900524X

Mtunguja, M. K., Laswai, H. S., Kanju, E., Ndunguru, J., & Muzanila, Y. C. (2016). Effect of genotype and genotype by environment interaction on total cyanide content, fresh root, and starch yield in farmer-preferred cassava landraces in Tanzania. *Food Science & Nutrition*, *4*(6), 791–801. https://doi.org/10.1002/fsn3.345

Mubalama, J. M., Ayagirwe, R. B. B., Martin, P., Nguezet, D., Mondo, J. M., Irenge, A. B., Dontsop-Nguezet, P. M., Karume, K., Njukwe, E., Mapatano, S. M., Zamukulu, P. M., Basimine, G. C., Musungayi, E. M., Mbusa, H. K., Kazamwali, L. M., Civava, R., & Mushagalusa, G. N. (2019). Determinants of adoption and farmers' preferences for cassava varieties in Kabare territory, eastern Democratic Republic of Congo. *American Journal of Rural Development*, *7*(2), 44–52. https://doi.org/10.12691/ajrd-7-2-1

Muhindo, H., Yasenge, S., Casinga, C., Songbo, M., Dhed'a, B., Alicai, T., Pita, J., & Monde, G. (2020). Incidence, severity and distribution of cassava brown streak disease in northeastern Democratic Republic of Congo. *Cogent Food & Agriculture*, *6*(1), 1–13. https://doi.org/10.1080/23311932.2020.1789422

Mushumbusi, C. B. (2018). *Cyanide levels in raw sweet cassava varieties and peoples perception on cyanide poisoning in Kagera and Morogoro regions of Tanzania*. Sokoine University of Agriculture.

Mutisya, D. L., Khamala, C. P. M., El Banhawy, E. M., Kariuki, C. W., & Ragwa, S. (2013). Cassava variety tolerance to spider mite attack in relation to leaf cyanide level. *Journal of Biology, Agriculture and Healthcare*, *3*(5), 24–30. http://www.iiste.org/Journals/index.php/JBAH/article/view/5365

Nambisan, B. (2011). Strategies for elimination of cyanogens from cassava for reducing toxicity and improving food safety. *Food and Chemical Toxicology*, *49*(3), 690–693. https://doi.org/10.1016/j.fct.2010.10.035

Ndubuisi, N. D., & Chidiebere, A. C. U. (2018). Cyanide in cassava: a review. *International Journal of Genomics and Data Mining*, *3*(1), 1–10. https://doi.org/10.29011/2577-0616.000118

Nebiyu, A., & Getachew, E. (2011). Soaking and drying of cassava roots reduced cyanogenic potential of three cassava varieties at Jimma, Southwest Ethiopia. *African Journal of Biotechnology*, *10*(62), 13465–13469. https://doi.org/10.5897/ajb10.2636

Nhassico, D., Muquingue, H., Cliff, J., Cumbana, A., & Bradbury, H. J. (2008). Rising African cassava production, diseases due to high cyanide intake and control measures. *Journal of the Science of Food and Agriculture*, *88*(22), 2043–2049. https://doi.org/10.1002/jsfa

Njukwe, E., & Kirscht, H. (2013). Farmers perception and criteria for cassava variety preference in Cameroon. *African Study Monographs*, *34*(4), 221–234. https://doi.org/10.14989/185091

Nnopuechi, J. (2021). *The history of recent droughts in Africa (1980–2020)*. Consequences, Responses and Lessons Learned. https://secaangola.hypotheses.org

Nuwamanya, E., Baguma, Y., Atwijukire, E., Acheng, S., & Alicai, T. (2015). Effect of cassava brown streak disease (CBSD) on cassava (Manihot esculenta Crantz) root storage components, starch quantities and starch quality properties. *International Journal of Plant Physiology and Biochemistry*, *7*, 12–22. https://doi.org/10.5897/IJPPB2015.0227

Nuwamanya, E., Rubaihayo, P. R., Mukasa, S., Samuel, K., Hawumba, J. F., & Baguma, Y. (2014). Biochemical and secondary metabolites changes under moisture and temperature stress in cassava (*Manihot esculenta* Crantz). *African Journal of Biotechnology*, *13*(31), 3173–3186. https://doi.org/10.5897/ajb2014.13663

Nwokoro, C. C. (2021). *Improvements to cassava-maize intercropping systems in southern Nigeria* (Issue 27677). https://doi.org/10.3929/ethz-b-000504365

Obigbesan, G. O. (1977). Investigations on Nigerian root and tuber crops: Response of cassava cultivars to potassium on starch yields, HCN content and nutrient uptake of cassava cultivars (*Manihot esculenta*). *The Journal of Agricultural Science Cambridge*, *89*(1), 23–27. https://doi.org/10.1017/S0021859600027155

Ojo, S. O., & Ogunyemi, A. I. (2014). Analysis of factors influencing the adoption of improved cassava production technology in Ekiti state, Nigeria. *International Jounal of Agricultural Sciences and Natural Resources*, *1*(3), 40–44. http://www.aascit.org/journal/ijasnr

Okwu, D., & Awurum, A. (2008). Effects of fertiliser application on the chemical composition of cassava tubers and their garri product. *Journal of Applied Chemistry and Agricultural Research*, *7*(1), 23–36. https://doi.org/10.4314/jacar.v7i1.41133

Oluwole, O. S. A., Onabolu, A. O., Link, H., & Rosling, H. (2000). Persistence of tropical ataxic neuropathy in a Nigerian community. *Journal of Neurology, Neurosurgery, and Psychiatry*, *69*, 96–101. https://doi.org/10.1136/jnnp.69.1.96

Omar, N. F., Hassan, S. A., Yusoff, U. K., Abdullah, N. A. P., Wahab, P. E. M., & Sinniah, U. R. (2012). Phenolics, flavonoids, antioxidant activity and cyanogenic glycosides of organic and mineral-base fertilized cassava tubers. *Molecules*, *17*(3), 2378–2387. https://doi.org/10.3390/molecules17032378

Omongo, C. A., Kawuki, R., Bellotti, A. C., Alicai, T., Baguma, Y., Maruthi, M. N., Bua, A., & Colvin, J. (2012). African cassava whitefly, Bemisia tabaci, resistance in African and south American cassava genotypes. *Journal of Integrative Agriculture*, *11*(2), 327–336. https://doi.org/10.1016/S2095-3119(12)60017-3

Onabolu, A., Bokanga, M., Tylleskär, T., & Rosling, H. (2001). High cassava production and low dietary cyanide exposure in midwest Nigeria. *Public Health Nutrition*, *4*(1), 3–9. https://doi.org/10.1079/phn200049

Opata, P. I., Okorie, O. J., Iwuchukwu, J. C., Ume, C. O., & Oyinbo, O. (2021). Adoption of improved cassava varieties in Nigeria: Insights from DNA fingerprinting versus self-reporting varietal identification approaches. *Outlook on Agriculture*, *50*(3), 269–276. https://doi.org/10.1177/0030727021990032

Opoku-Nkoom, W., Asibey-Berko, E., & Lartey, A. (2013). Cyanide content of leaves of commonly consumed cassava varieties from three geographical regions of Ghana. *Journal of Food Science and Engineering*, *3*, 648–656. https://doi.org/10.17265/2159-5828/2013.12.002

Orek, C. (2024). A review of management of major arthropod pests affecting cassava production in sub-Saharan Africa. *Crop Protection*, *175*(2023), 106465. https://doi.org/10.1016/j.cropro.2023.106465

Osei, M. K., Taah, K. J., Berchie, J. N., & Osei, C. K. (2009). A survey of cassava (*Manihot esculenta* Crantz) planting materials in storage: A case study in two communities in the ejisu district of ashanti region, Ghana. *Journal of Agronomy*, *8*(4), 137–140. https://doi.org/10.3923/ja.2009.137.140

Osewe, M., Liu, A., & Han, J. (2021). Variety traits and sustainable food security: The role of improved cassava varieties in Kenya. *Chemical Engineering Transactions*, *89*, 355–360. https://doi.org/10.3303/CET2189060

Owusu, V., & Emmanuel, D. (2012). Adoption of improved cassava varieties in Ghana. *Agricultural Journal*, *7*(2), 146–151. https://www.ajol.info/index.php/gjas/article/view/116242

Parmar, A., Sturm, B., & Hensel, O. (2017). Crops that feed the world: Production and improvement of cassava for food, feed, and industrial uses. *Food Security*, *9*(5), 907–927. https://doi.org/10.1007/s12571-017-0717-8

Peprah, B. B., Parkes, E. Y., Harrison, O. A., van Biljon, A., Steiner-Asiedu, M., & Labuschagne, M. T. (2020). Proximate composition, cyanide content, and carotenoid retention after boiling of provitamin A-rich cassava grown in Ghana. *Food*, *9*(12), 1800. https://doi.org/10.3390/foods9121800

Pereira, J. F., Seigler, D. S., & Splittstoesser, W. E. (1981). Cyanogenesis in sweet and bitter cultivars of cassava. *HortScience*, *16*(6), 776–777. https://journals.ashs.org/hortsci/view/journals/hortsci/16/6/article-p776.xml

Pereira Soares, D. O., Dutra Pinto, K. G., da Gama, L. A., Ferreira, C. C., Bhowmik, P. C., & Figueiredo Albertino, S. M. (2021). Physical properties of soil and glyphosate residue as a function of cassava weed management by cover crops in the Amazon ecosystem. *HortScience*, *56*(9), 1053–1058. https://doi.org/10.21273/HORTSCI15895-21

Polthanee, A., & Srisutham, M. (2017). Supplementary irrigation for cassava planted in the late rainy season of northeastern Thailand. *Asian Journal of Crop Science*, *9*(4), 100–108. https://doi.org/10.3923/ajcs.2017.100.108

Quinn, A. A., Myrans, H., & Gleadow, R. M. (2022). Cyanide content of cassava food products available in Australia. *Food*, *11*, 1384. https://doi.org/10.3390/foods11101384

Ratto, F., Bruce, T., Chipabika, G., Mwamakamba, S., Mkandawire, R., Khan, Z., Mkindi, A., Pittchar, J., Sallu, S. M., Whitfield, S., Wilson, K., & Sait, S. M. (2022). Biological control interventions reduce pest abundance and crop damage while maintaining natural enemies in sub-Saharan Africa: A meta-analysis. *Proceedings of the Royal Society B: Biological Sciences*, *289*(1988), 20221695. https://doi.org/10.1098/rspb.2022.1695

Ricker-Gilbert, J. (2020). Inorganic fertiliser use among smallholder farmers in sub-Saharan Africa: Implications for input subsidy policies. In S. G. Paloma, L. Riesgo, & K. Louhichi (Eds.), *The role of smallholder farms in food and nutrition security* (1st ed., pp. 81–98). Springer Nature. https://doi.org/10.1007/978-3-030-42148-9_5

Riis, L., Bellotti, A. C., Bonierbale, M., & O'Brien, G. M. (2003). Cyanogenic potential in cassava and its influence on a generalist insect herbivore *Cyrtomenus bergi* (Hemiptera: Cydnidae). *Journal of Economic Entomology*, *96*(6), 1905–1914. https://doi.org/10.1093/jee/96.6.1905

Rosenthal, D. M., Slattery, R. A., Miller, R. E., Grennan, A. K., Cavagnaro, T. R., Fauquet, C. M., Gleadow, R. M., & Ort, D. R. (2012). Cassava about-FACE: Greater than expected yield stimulation of cassava (Manihot esculenta) by future CO_2 levels. *Global Change Biology*, *18*(8), 2661–2675. https://doi.org/10.1111/j.1365-2486.2012.02726.x

Ruiz-Vera, U. M., De Souza, A. P., Ament, M. R., Gleadow, R. M., & Ort, D. R. (2021). High sink strength prevents photosynthetic down-regulation in cassava grown at elevated CO2 concentration. *Journal of Experimental Botany*, *72*(2), 542–560. https://doi.org/10.1093/jxb/eraa459

Saggafu, S. M., Saha, H. M., & Mwololo, J. (2019). Effects of weeding intensity on cyanide content of cassava root tubers. *Global Scientific Journals*, *7*(8), 337–352. www.globalscientificjournal.com

Sangakkara, U., Attanayake, K., Gajanayake, J., & Bandaranayake, P. (2004). Impact of mulches on growth and yields of cassava and sweet potato in tropical Asia. *Agronomy Australia Proceedings*, *1645*, 1–76. http://agronomyaustraliaproceedings.org

Sanoussi, A. F., Loko, L. Y., Ahissou, H., Adjahi, A. K., Orobiyi, A., Agré, A. P., Azokpota, P., Dansi, A., & Sanni, A. (2015). Diversity, physicochemical and technological characterization of elite cassava (*Manihot esculenta* Crantz) cultivars of Bantè, a district of Central Benin. *Scientific World Journal*, *2015*, 674201. https://doi.org/10.1155/2015/674201

Santisopasri, V., Kurotjanawong, K., Chotineeranat, S., Piyachomkwan, K., Sriroth, K., & Oates, C. G. (2001). Impact of water stress on yield and quality of cassava starch. *Industrial Crops and Products*, *13*(2), 115–129. https://doi.org/10.1016/S0926-6690(00)00058-3

Sanusi, O. R., Lordbanjou, D.-T., Ibrahim, A. O., Abubakar, B. M., & Oke, O. O. (2022). Tropical plant species and technological interventions for improvement. In S. M. Khan (Ed.), *Tropical plant species and technological interventions for improvement* (Vol. *11*, pp. 1–20). IntechOpen. https://doi.org/10.5772/intechopen.104677

Schmidt, F. B., Cho, S. K., Olsen, C. E., Yang, S. W., Møller, B. L., & Jørgensen, K. (2018). Diurnal regulation of cyanogenic glucoside biosynthesis and endogenous turnover in cassava. *Plant Direct*, *2*(2), e00038. https://doi.org/10.1002/pld3.38

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M., & Reinhardt, J. (2017). Climate change impacts in sub-Saharan Africa: From physical changes to their social repercussions. *Regional Environmental Change*, *17*(6), 1585–1600. https://doi.org/10.1007/s10113-015-0910-2

Shackelford, G. E., Haddaway, N. R., Usieta, H. O., Pypers, P., Petrovan, S. O., & Sutherland, W. J. (2018). Cassava farming practices and their agricultural and environmental impacts: A systematic map protocol. *Environmental Evidence*, *7*, 1–7. https://doi.org/10.1186/s13750-018-0142-2

Sheat, S., & Winter, S. (2023). Developing broad-spectrum resistance in cassava against viruses causing the cassava mosaic and the cassava brown streak diseases. *Frontiers in Plant Science*, *14*, 1042701. https://doi.org/10.3389/fpls.2023.1042701

Shongwe, M. E., Van Oldenborgh, G. J., Van den Hurk, B., & van Aalst, M. (2011). Projected changes in mean and extreme precipitation in Africa under global warming. Part II: East Africa. *Journal of Climate*, *24*(14), 3718–3733. https://doi.org/10.1175/2010JCLI2883.1

Siddiqi, O. K., Kapina, M., Kumar, R., Ngomah Moraes, A., Kabwe, P., Mazaba, M. L., Hachaambwa, L., Ng'uni, N. M., Chikoti, P. C., Morel-Espinosa, M., Jarrett, J. M., Baggett, H. C., & Chizema-Kawesha, E. (2020). Konzo outbreak in the Western Province of Zambia. *Neurology*, *94*(14), E1495–E1501. https://doi.org/10.1212/WNL.0000000000009017

Sillmann, J., Kharin, V. V., Zwiers, F. W., Zhang, X., & Bronaugh, D. (2013). Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *Journal of Geophysical Research-Atmospheres*, *118*(6), 2473–2493. https://doi.org/10.1002/jgrd.50188

Spencer, D., & Ezidinma, C. (2017). Cassava cultivation in sub-Saharan Africa. In C. Hershey & Clair (International Center for Tropical Agriculture) (Eds.), *Achieving sustainable cultivation of cassava* (1st ed., pp. 123–148). Burleigh Dodds Series in Agricultural Science. https://doi.org/10.4324/9781351114318

Srinivasan, R., Tamò, M., & Subramanian, S. (2022). The case for integrated pest management in Africa: Transition from a pesticide-based approach. *Current Opinion in Insect Science*, *54*, 100970. https://doi.org/10.1016/j.cois.2022.100970

Tabaglio, V., Fiorini, A., Ndayisenga, V., Ndereyimana, A., Minuti, A., Nyembo Nyembo, R., Nyembo Ngoy, D., & Bertoni, G. (2023). Sustainable intensification of cassava production towards food security in the Lomami Province (DR Congo): Role of planting method and landrace. *Agronomy*, *13*(1), 228. https://doi.org/10.3390/agronomy13010228

Tafesse, A., Mena, B., Belay, A., Aynekulu, E., Recha, J. W., Osano, P. M., Darr, D., Demissie, T. D., Endalamaw, T. B., & Solomon, D. (2021). Cassava production efficiency in Southern Ethiopia: The parametric model analysis. *Frontiers in Sustainable Food Systems*, *5*, 758951. https://doi.org/10.3389/fsufs.2021.758951

Tang, X., Zhong, R., Jiang, J., He, L., Huang, Z., Shi, G., Wu, H., Liu, J., Xiong, F., Han, Z., Tang, R., & He, L. (2020). Cassava/peanut intercropping improves soil quality via rhizospheric microbes increased available nitrogen content. *BMC Biotechnology*, *20*(1), 1–11. https://doi.org/10.1186/s12896-020-00606-1

Taylor, N., Chavarriaga, P., Raemakers, K., Siritunga, D., & Zhang, P. (2004). Development and application of transgenic technologies in cassava. *Plant Molecular Biology*, *56*(4), 671–688. https://doi.org/10.1007/s11103-004-4872-x

Tchacondo, T., Karou, S., Osseyi, E., Agban, A., Bawa, L., Atcha, A., Soumana, K., Assignon, K., Kpemoua, A., & De Souza, C. (2011). Effect of harvest and cook processing on cyanides content of cassava cultivars and cassava-based dough consumed in Lomé, Togo. *Advance Journal of Food Science and Technology*, *3*(5), 399–403. https://maxwellsci.com/print/ajfst/v3-399-403.pdf

Teles, F. F. F. (2002). Chronic poisoning by hydrogen cyanide in cassava and its prevention in Africa and Latin America. *Food and Nutrition Bulletin*, *23*(4), 407–412. https://doi.org/10.1177/156482650202300418

Theriault, V., & Smale, M. (2021). The unintended consequences of the fertiliser subsidy program on crop species diversity in Mali. *Food Policy*, *102*(June), 102121. https://doi.org/10.1016/j.foodpol.2021.102121

Tivana, L., Bvochora, J., Mutukumira, A., Owens, J., & Zvauya, R. (2007). Heap fermentation of cassava (*Manihot esculenta* Crantz) in Nampula province, Mozambique. *Proceedings of the 13th International Society for Tropical Root Crops (ISTRC)*, 445–450. http://www.istrc.org/images/Documents/Symposiums/Thirteenth/p2_tivana.pdf

Tor-Agbidye, J., Palmer, V. S., Lasarev, M. R., Craig, A. M., Blythe, L. L., Sabri, M. I., & Spencer, P. S. (1999). Bioactivation of cyanide to cyanate in sulfur amino acid deficiency: Relevance to neurological disease in humans subsisting on cassava. *Toxicological Sciences*, *50*(2), 228–235. https://doi.org/10.1093/toxsci/50.2.228

Trisos, C. H., Adelekan, I. O., Totin, E., Ayanlade, A., Efitre, J., Gemeda, A., Kalaba, K., Lennard, C., Masao, C., Mgaya, Y., Ngaruiya, G., Olago, D., Simpson, N. P., & Zakieldeen, S. (2022). Nine principles for encouraging a context-driven, inclusive and proactive approach to planning for climate risk in African cities. In *Climate change 2022: Impacts, adaptation and vulnerability*. Cambridge University Press. https://doi.org/10.1017/9781009325844.011.1286

Tshala-Katumbay, D. D., Ngombe, N. N., Okitundu, D., David, L., Westaway, S. K., Boivin, M. J., Mumba, N. D., & Banea, J.-P. (2016). Cyanide and the human brain. Perspectives from a model of food (cassava) poisoning. *Annals of the New York Academy of Sciences*, *1378*(1), 50–57. https://doi.org/10.1111/nyas.13159

Tumwesigye, S. K., Baguma, Y., Kyamuhangire, W., & Mpango, G. (2006). Association between accumulation of total cyanogens and progression of cassava mosaic disease in cassava (*Manihot*

esculenta Crantz). *Uganda Journal of Agricultural Sciences*, *12*(1), 13–21. https://nru.uncst.go.ug/handle/123456789/3622
United Nations Department of Economic and Social Affairs, P. D. (2022). *World population prospects 2022: Summary of results*. https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf
Vandegeer, R., Miller, R. E., Bain, M., Gleadow, R. M., & Cavagnaro, T. R. (2013). Drought adversely affects tuber development and nutritional quality of the staple crop cassava.Pdf. *Functional Plant Biology*, *40*, 195–200. https://doi.org/10.1071/FP12179
Wasonga, D. O., Kleemola, J., Alakukku, L., & Mäkelä, P. S. (2020a). Potassium fertigation with deficit irrigation improves the nutritive quality of cassava. *Frontiers in Sustainable Food Systems*, *4*, 575353. https://doi.org/10.3389/fsufs.2020.575353
Wasonga, D. O., Kleemola, J., Alakukku, L., & Mäkelä, P. S. A. (2020b). Growth response of cassava to deficit irrigation and potassium fertigation during the early growth phase. *Agronomy*, *10*(3), 321. https://doi.org/10.3390/agronomy10030321
Wasonga, D. O., Kleemola, J., Alakukku, L., & Mäkelä, P. S. (2020c). Growth response of cassava to deficit irrigation and potassium fertigation during the early growth phase. *Agronomy*, *10*(3), 321. https://doi.org/10.3390/agronomy10030321
Wasonga, D. O., Kleemola, J., Alakukku, L., & Mäkelä, P. S. (2020d). Potassium fertigation with deficit irrigation improves the nutritive quality of cassava. *Frontiers in Sustainable Food Systems*, *4*, 575353. https://doi.org/10.3389/fsufs.2020.575353
Wassie, A. S. (2020). Cassava production and field Management in Ethiopia. *Bryanhousepub.Org*, *2*(1), 31–40. http://www.bryanhousepub.org/src/static/pdf/JAH-2020-2-1_7.pdf
Wossen, T., Alene, A., Abdoulaye, T., Feleke, S., Rabbi, I. Y., & Manyong, V. (2019). Poverty reduction effects of agricultural technology adoption: The case of improved cassava varieties in Nigeria. *Journal of Agricultural Economics*, *70*(2), 392–407. https://doi.org/10.1111/1477-9552.12296
Wossen, T., Girma, G., Abdoulaye, T., Rabbi, I., Olanrewaju, A., Alene, A., Feleke, S., Kulakow, P., Asumugha, G., Abass, A., & Manyong, V. (2017). *The cassava monitoring survey in Nigeria*. International Institute for Tropical Agriculture (IITA). https://www.iita.org/wp-content/uploads/2017/03
Zhao, P., Liu, P., Shao, J., Li, C., Wang, B., Guo, X., Yan, B., Xia, Y., & Peng, M. (2015). Analysis of different strategies adapted by two cassava cultivars in response to drought stress: Ensuring survival or continuing growth. *Journal of Experimental Botany*, *66*(5), 1477–1488. https://doi.org/10.1093/jxb/eru507

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Nyaika, J., Abayomi, L., Parmar, A., & Coast, O. (2024). Cyanide in cassava: Understanding the drivers, impacts of climate variability, and strategies for food security. *Food and Energy Security*, *13*, e573. https://doi.org/10.1002/fes3.573