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REVIEW

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Sustainable sweetpotato production in the United States: Current status, challenges, and opportunities

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Abstract

Sweetpotato (*Ipomoea batatas* L.) is an important staple crop cultivated in over 100 countries, and the storage roots and vines provide food for humans and livestock. Sweetpotato consumption and demand for its value-added products have increased significantly in the last two decades and have led to new cultivar development, expansion in acreage, and increased demand in the United States and its export markets. Despite the known nutritional components and other health benefits, further research is needed to characterize the genetic diversity and chemical composition related to their storage root qualities, essential in developing consumer-preferred cultivars that offer host plant resistance against pests and pathogens. There is a critical need for research on non-pesticidal control approaches that can provide safe, effective, economical, sustainable, and environmentally sound pest and disease management techniques, especially for socially disadvantaged small farmers in the United States. Moreover, climate change can significantly impact future production practices and

Abbreviations: CIP, international potato center; IPM, integrated pest management; PPN, plant parasitic nematode; RKN, root-knot nematode; RN, reniform nematode; WU, water use; WUE, water use efficiency.

yield and may directly or indirectly affect crop pests, weeds, and diseases. In this review, we discuss the current status, challenges, and future approaches associated with sweetpotato production practices; health-promoting properties of sweetpotato cultivars; value-added products; genetic diversity and germplasm; pest and disease management; weed and water management; pollination ecology; and other agronomic and cultural practices that may impact sustainable sweetpotato production by small-scale, organic, and large-scale growers.

1 | INTRODUCTION

Sweetpotato, *Ipomoea batatas* L., is a favorite staple crop in many cultures and is established worldwide (Mukhopadhyay et al., 2011; Woolfe, 1992). It is a dicotyledonous plant belonging to the family Convolvulaceae and a root crop important for food security (Barkessa, 2018). Worldwide, sweetpotato is the seventh most important food crop after rice, wheat, potato, maize, barley, and cassava (Muhammad et al., 2012; Neela & Fanta, 2019). From 2018 to 2021, the estimated global production ranged from 88.7 to 92.3 Mt, where Asian countries produced 61.5%–66.6% and African countries 28.6%–33.7% of the global production (FAOSTAT, 2023). Sweetpotato is a valuable crop because it is regarded as one of the most nutritious vegetables and produces more food per hectare than any other crop. It is also a versatile crop because the storage roots can be consumed or processed into value-added foods (e.g., fries, chips, starch, alcohol) and industrial products (e.g., fuel and chemicals) plus the vines can be consumed or used as livestock feed (Clark et al., 2012; Loebenstein & Thottappilly, 2009; Zhang et al., 2013).

North Carolina is the leading sweetpotato producer by tonnage in the United States, followed by California and Mississippi (USDA-NASS, 2023). Despite the increase in acreage and cultivars, the sweetpotato industry faces many challenges associated with yield losses due to weather extremes, pest and disease incidence, storage and processing issues, and underuse of value-added products. Sweetpotato production and the number of farmers (small, large, conventional, and organic) interested in sweetpotato cultivation are growing. However, the economic viability of sweetpotato production can be undermined due to susceptibility of commercial cultivars to biotic (i.e., diseases, insect pests, and weeds) and abiotic (i.e., environmental variability, low fertility) factors that can dramatically influence yield, quality, and marketability. Management practices such as pest and disease management for sweetpotato can be very expensive, add substantially to market prices, and have adverse environmental and health effects. Socially disadvantaged small farmers are more vulnerable to losses due to a lack of integrated pest management (IPM) knowledge, limited resources, and challenges in managing plant pests, as most IPM projects focus on large farms (Collins, 2022). Hence, there is a critical need for research on nonchemical control approaches that can provide effective, sustainable, and environmentally sound pest and disease management techniques for socially disadvantaged small farmers in the United States. Nonetheless, sweetpotato is an ideal crop for limited resource farmers as it produces more biomass and nutrients per hectare than any other food crop globally without fertilizers and irrigation (Loebenstein & Thottappilly, 2009) and host resistance to the common plant pests is readily available (Jones et al., 1986). The current status, challenges, and solutions for the US sweetpotato industry need to be identified and discussed to support sweetpotato cultivation.

This is an extensive review on the US sweetpotato industry from subject matter experts to address these needs. The topics that will be addressed are (1) health-promoting properties of sweetpotato cultivars, value-added products, and consumer preferences; (2) pollination ecology and the foraging landscape in sweetpotato ecosystems; (3) pest and disease management; (4) weed management; (5) water management; (6) impact of climate change on global sweetpotato production; and (7) current limitations and challenges for small-scale and organic farmers. Also, we discuss how these agronomic and cultural practices impact sustainable production by small-scale, organic, and large-scale growers (Figure 1). These topics impact all US sweetpotato industry stakeholders and demonstrate the need for increased research efforts to support this industry.

2 | HEALTH-PROMOTING PROPERTIES OF SWEETPOTATO CULTIVARS AND CONSUMER ACCEPTANCE

2.1 | Health benefits of sweetpotatoes

The sweetpotato is a nutritious vegetable with substantial quantities of essential vitamins and minerals and health-promoting phytonutrients. For example, a baked medium-sized sweetpotato (114 g) is high in copper, manganese, and vitamins A, C, B1, B2, B3, B5, and plus B6 and is a good

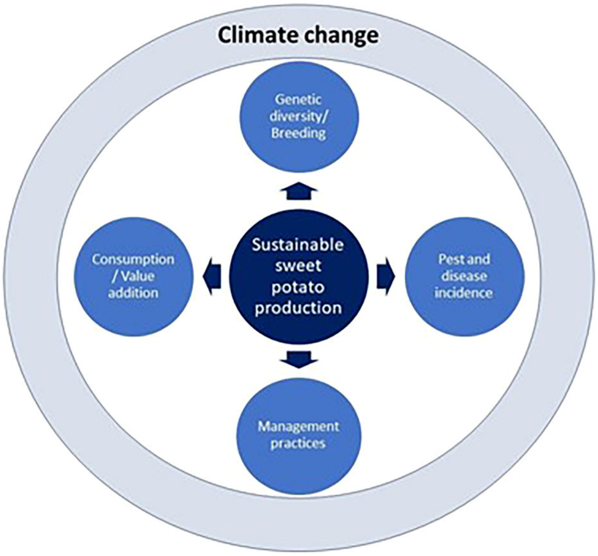

FIGURE 1 Interactions of different factors that may contribute to the sustainable production and consumption of sweetpotatoes. All these factors and changes in weather patterns can influence the sweetpotato production, quality, and yield by small-scale, organic, and large-scale producers.

Core Ideas

- Sweetpotato (*Ipomoea batatas* L.) is an important staple crop cultivated in over 100 countries.
- US sweetpotato industry faces many production challenges, including pest and diseases, as well as climate change extremes.
- A comprehensive review by subject matter experts on the challenges of US sweetpotato industry is not available.
- This review evaluates the current situation, challenges, and future approaches for improving sweetpotato production.
- Also, current and future impacts of climate change on global sweetpotato production and demand are discussed.

source of potassium (USDA-ARS, 2019). Sweetpotatoes are also a good source of fiber, which has been shown to improve the gut microbiome and promote beneficial immunological responses (Liu et al., 2020; Tang et al., 2018).

Sweetpotatoes flesh can be colored orange, yellow, white, purple, and shades in between. Orange-fleshed sweetpotatoes garner their color from β-carotene—a carotenoid with antioxidant and pro-vitamin A activities. About 90% of the carotenoids in Covington, a popular orange-fleshed cultivar in the United States, is β-carotene (Grace et al., 2014). β-Carotene is a unique carotenoid because it has 100% provitamin A activity, and one molecule can be converted into two vitamin A molecules in the body. This makes orange-fleshed sweetpotatoes exceptionally nutritious, particularly in regions suffering from vitamin A deficiencies (Boy & Miloff, 2009). Yellow-fleshed sweetpotatoes also contain carotenoids but in lower concentrations with ~30%–60% being β-carotene (Grace et al., 2014). Carotenoids in the diet reduce metabolic oxidative stress, are beneficial for the immune system, and reduce cancer and cardiovascular risks (Rodriguez-Amaya, 2015).

The color of purple sweetpotatoes is due to anthocyanins, a class of pH-sensitive, water-soluble compounds commonly found in red-, blue-, and purple-colored fruits and vegetables (Wu et al., 2006). Anthocyanins are polyphenols with powerful antioxidant activities and are generally associated with health-promoting benefits. Purple sweetpotatoes and extracts thereof have been associated with antioxidant activity, anticarcinogenic effects, anti-inflammatory properties, blood glucose modulation, immunomodulatory activity, plus liver and kidney protection (Albuquerque et al., 2019; Jiang et al., 2022). Purple sweetpotato anthocyanin content can vary, but Stokes Purple, one of the leading purple cultivars in the United States, has similar antioxidant levels on a fresh weight basis as antioxidant-rich fruits, such as grapes, strawberries, and raspberries (Truong et al., 2010; Wu et al., 2006). In addition to differences in total anthocyanin concentration, the types of anthocyanins also affect purple sweetpotato bioactivities (Esatbeyoglu et al., 2017; Hu et al., 2016). There is a wealth of data demonstrating sweetpotatoes are a healthy food (Albuquerque et al., 2019). Therefore, developing new varieties and technologies that increase sweetpotato consumption in the United States would benefit both the sweetpotato industry and the health of the American people.

2.2 | Common US sweetpotato cultivars

The most popular type of sweetpotatoes in the United States are the sweet, moist, light-skinned, and orange-fleshed cultivars Covington and Beauregard (Table 1). In some parts of the country, these varieties are marketed as "yams," a term introduced by southern US sweetpotato producers to distinguish orange-fleshed cultivars from the white/cream-fleshed varieties of the mid-20th century. To avoid confusion with the true yam (Dioscoreaceae family), the U.S. Department of Agriculture (USDA) now requires that the word "sweetpotato" is present on the label (Smith et al., 2009; Truong et al., 2018). Covington and Beauregard are the current dominant cultivars of this market category, but Orleans is a newer orange-fleshed cultivar that has greater yields than Beauregard (La Bonte et al., 2012) and is starting to capture a portion of the

TABLE 1 Characteristics and compositions of commonly grown US sweetpotato cultivars.

Cultivar	Flesh color[a]	Skin color[a]	*n*	Dry matter %	Starch (g·100 g^{-1} FW)	Sucrose (g·100 g^{-1} FW)	Glucose + fructose (g·100 g^{-1} FW)	β-Carotene (μg·g^{-1} FW)	Monomeric anthocyanins (μg·g^{-1} FW)
Bayou Belle	Orange	Red/purple	76	20.6 ± 1.3	6.5 ± 1.0	2.4 ± 0.4	2.2 ± 0.4	69.4 ± 18.2	ND
Beauregard	Orange	Light rose	205	21.9 ± 1.7	9.5 ± 1.4	1.5 ± 0.4	1.6 ± 0.4	72.9 ± 19.5	ND
Covington	Orange	Light rose	263	22.2 ± 1.5	7.8 ± 1.4	2.9 ± 0.4	1.0 ± 0.3	71.6 ± 19.1	ND
Jewel	Orange	Copper	8	22.7 ± 2.2	9.2 ± 2.2	1.8 ± 0.3	1.4 ± 0.3	73.1 ± 15.8	ND
Orleans	Orange	Light rose	12	21.1 ± 1.3	9.2 ± 1.1	1.4 ± 0.3	1.7 ± 0.2	70.7 ± 20.2	ND
Murasaki-29	White	Dark purple	28	28.1 ± 1.2	16.0 ± 1.9	2.1 ± 0.2	0.4 ± 0.2	ND	ND
Bonita	White/cream	Light tan	23	26.3 ± 1.3	14.3 ± 2.0	1.6 ± 0.3	0.8 ± 0.2	ND	ND
Purple Majesty	Dark purple	Dark purple	41	28.5 ± 1.0	15.3 ± 1.4	1.3 ± 0.4	1.1 ± 0.3	–[b]	773.0 ± 95.2
Purple Splendor	Purple	Dark purple	57	28.3 ± 1.0	16.0 ± 1.6	1.8 ± 0.2	0.6 ± 0.2	–[b]	627.0 ± 114.9
Stokes Purple	Purple	Dark purple	39	28.6 ± 1.3	17.5 ± 2.0	1.5 ± 0.3	0.4 ± 0.2	–[b]	498.5 ± 160.5

Note: Compositions are predictions from near-infrared spectroscopy (NIRS) scans of roots that were stored 6–10 weeks after harvest from 2017 to 2021. Data provided by the North Carolina State University Sweetpotato and Potato Breeding and Genetics Programs.

Abbreviations: FW, fresh weight basis; ND, not detected.

[a]Sweetpotato characteristic descriptions from LSU and NCSU sweetpotato breeding programs (Arnold, 2016; Sweetpotato and Potato Breeding and Genetics Programs, 2022).

[b]β-Carotene cannot be predicted in purple-fleshed sweetpotatoes by NIRS using the current models.

market. Vermillion and Diane are also orange-fleshed cultivars but have thicker red-purple skin and are sometimes labeled as “red-yams” or “Garnet” at the point of sale. Bayou Belle is another high-yielding cultivar in this market category but is mainly grown for processing (Table 1). The “red-yam” is prevalent in California and often receives higher prices than the “yam” sweetpotatoes (Stoddard et al., 2013).

Cream/yellow-fleshed sweetpotatoes with light skin tend to have higher dry matter and a less moist texture than orange-fleshed cultivars. They are marketed as “Jersey Sweets” particularly in the Northeastern United States and “sweets” or “sweetpotatoes” in the western states and provinces of the United States and Canada (Smith et al., 2009; Stoddard et al., 2013). Most of these sweetpotatoes are grown in California and typically sold at West Coast retailers, high-end grocers, and ethnic markets (Don La Bonte, personal communication, 2023). Bonita is a popular cultivar in this category, replacing O’Henry, a cream-fleshed mutant of Beauregard. The “Oriental”/“Japanese” sweetpotato market types have white/cream flesh with dark purple skin, and Murasaki-29 is the dominant cultivar of this type in the United States (Stoddard et al., 2013).

Purple sweetpotatoes are currently a niche market in the United States, and the most common cultivars are Stokes Purple, with deep purple-flesh and skin, and Okinawan, a light purple-flesh and light brown skin cultivar. However, yields of these varieties are less than other sweetpotatoes. The North Carolina State University sweetpotato breeding program released two purple-fleshed sweetpotato cultivars in 2021—Purple Majesty and Purple Splendor (Sweetpotato and Potato Breeding and Genetics Programs, 2022). These cultivars have superior yields, shapes, and growing condition adaptability with eating quality similar to Stokes Purple (Yencho & Pecota, 2022a, 2022b). Purple sweetpotatoes tend to have a dry texture and unique flavor characteristics such as vanilla aroma and more bitter and umami tastes, which were objectionable in a North Carolina consumer acceptance study (Leksrisompong et al., 2012). Despite purple sweetpotatoes having a niche market, there is still a need to develop purple sweetpotato cultivars that are more favorable to the US population. This would require an understanding of which compounds are health promoting as well as those inducing undesirable flavors; thus, more food science and breeding research is needed for the development of healthy and tasty purple sweetpotatoes.

2.3 | Sweetpotato eating quality

Consumer preferences for sweetpotato vary within the United States and around the world. The most popular type in the United States is the sweet, moist, orange-fleshed sweetpotato (Barkley et al., 2017; Leksrisompong et al., 2012; Smith et al., 2009), particularly in the Southeastern United States where most of the sweetpotatoes are produced. In the Western United States, the drier, yellow to white-fleshed varieties, along with moist-orange varieties, are preferred, whereas in Hawaii, dry, purple-fleshed varieties are preferred (Miyasaka et al., 2019; Smith et al., 2009; Stoddard et al., 2013). Differences in consumer preferences are also evident in other countries. For example, moist, orange-fleshed sweetpotatoes were disliked in South African and Ugandan consumer studies, while the white, sweet, dry/firm varieties were preferred (Laurie et al., 2013; Mwanga et al., 2020). Notwithstanding these general preferences, distinct market segments exist for sweetpotatoes, each with preferences for different sensory traits (Dery et al., 2021; Leksrisompong et al., 2012). This provides an opportunity to expand the overall market for sweetpotato by developing new cultivars and products that appeal to varied consumer segments. To better understand regional differences in consumer preference, a universal sweetpotato lexicon was developed to objectively evaluate sensory attributes (Nakitto et al., 2022). This lexicon was further developed to investigate the impact of intrinsic sweetpotato properties on eating quality of a wide range of US genotypes (Johanningsmeier et al., unpublished). This work will help breeders, growers, and processors make cultivar selections that match their markets’ preferences and develop new markets through varietal diversification.

2.4 | Processed sweetpotatoes: Value-added products

In the United States, sweetpotatoes that are sold to the consumer are typically US No. 1 grade, which are storage roots that have a uniform shape, are free of damage, and range in size between 5.1 and 8.9 cm in diameter and between 7.6 and 22.9 cm in length. Roots that are free from significant injuries (e.g., decay, cuts, and freezing) but exceed the defect and irregularity shape limit of the US No. 1 grade can be graded as US No. 2 or processor grades. Roots larger than the No. 1 criteria are called “jumbos.” Smaller roots that are 2.5–5.1 cm in diameter and 5.1–17.8 cm in length are called “canners.” The non-US No. 1 grade sweetpotatoes have lower value, and the high cost of harvesting can cause a substantial portion of potentially marketable sweetpotatoes to be unharvested. For example, it was estimated that 125 million kg of marketable sweetpotatoes were unharvested in the fields in North Carolina during the 2016 season (Johnson et al., 2018). Processed sweetpotato products are an avenue for value addition and utilization of off-grade sweetpotatoes. Common value-added sweetpotato products in the United States include French fries, chips, purées, dehydrated products, and canned forms. Other sweetpotato utilization options include livestock feed, flour, sugar, and starch production, which are more common in other sweetpotato-growing countries (Loebenstein & Thottappilly, 2009).

One of the most popular value-added products is sweetpotato fries. The popularity of this product has grown substantially over the past two decades, as indicated by the ~10- to 20-fold increase in the number of times the term “sweetpotato fries” was searched on Google in 2022 compared to 2004 (Google Trends, 2022). Sweetpotato fry production is also a great utilization of jumbos and roots with exterior visual defects. However, fries made from the current table-stock varieties lack a crispy exterior and typically require a batter; as with other foods cooked at high temperatures, they may contain acrylamide, a potentially carcinogenic neurotoxin (Zyzak et al., 2003). Food science and breeding research has been conducted to develop processes and genotypes that are better suited for sweetpotato fries to improve textures and minimize acrylamide formation. It was identified that sweetpotato composition (e.g., starch, moisture, sugar contents), amylase activities, as well as starch viscoelastic, structural, and thermal properties all affect fry textures (Allan & Johanningsmeier, 2022; Allan et al., 2021; Sato et al., 2018). In addition, acrylamide formation can be minimized in sweetpotato fries by processing aids that interfere with the reaction or by removal of acrylamide precursors—reducing sugars and free asparagine (Truong et al., 2014). A rapid and sensitive liquid chromatography with mass spectrometry (LC–MS/MS) method to quantify the limiting substrates for acrylamide formation has been developed for sweetpotatoes (Qiu et al., 2020). These findings plus ongoing research will help develop sweetpotato varieties better suited for fry production.

Sweetpotato chips are another popular value-added product in the United States and are also frequently produced using the lower starch, higher sugar, orange-fleshed cultivars. This can lead to challenges with acrylamide formation, excessive browning, weaker textures, and increased oil uptake. Sweetpotato chip-breaking force and oil contents have been correlated with dry matter content (Gao et al., 2014; Hagenimana et al., 1998), yet dry matter does not fully explain chip texture or oil content. Sweetpotato chips treated with enzymes that modified the cell wall polymers also experienced impacts on chip-breaking forces and oil uptake (Allan & Johanningsmeier, 2022). Therefore, both sweetpotato composition and cell wall polymer attributes should be considered in the selection of genotypes best suited for sweetpotato chips.

Sweetpotato purée is a value-added product that can use any shape or size of sweetpotato. It is also a versatile product that can be used as a biofortifying, healthy ingredient in many foods (e.g., baby food, beverages, soups, and baked goods). Sweetpotato purée is a low-acid food (pH 5.8–6.3) that requires intensive thermal processing for shelf stability when using traditional conductive heat transfer—causing notable nutrient and quality deterioration (Truong et al., 2018). However, a continuous flow microwave aseptic process developed by USDA-ARS and North Carolina State University scientists can reach the necessary internal temperature quickly and uniformly. This results in a shelf-stable product with similar color and viscosity as an unsterilized purée (Coronel et al., 2006; Simunovic et al., 2014). This advanced sterilization technology enabled the startup of Yamco, a sweetpotato purée microwave processing facility located in North Carolina, and an implementation in Kenya to produce orange-fleshed sweetpotato purées for biofortification of baked goods and other foods (North Carolina State University, 2020).

Sweetpotato dehydration is a value-added process that results in a shelf-stable product that can be used as an ingredient, ground into flour, or used for the pet food industry (Boyette & Macialek, 2012; Van Hal, 2000). Depending on the sweetpotato form (e.g., slices, dices, purée), sweetpotatoes can be dried using tunnel, oven, drum, or spray dryers (Truong et al., 2018). Solar drying is another standard method in rural sweetpotato-growing regions worldwide. However, a challenge with dehydrated orange-fleshed sweetpotatoes is β-carotene degradation, with most of it degrading within the first month of storage. This results in color and nutrient loss and generates off-flavors (Bechoff et al., 2011). Degradation rates can be slowed by blanching (De Moura et al., 2015), oxygen removal (Emenhiser et al., 1999), and antioxidant treatments (Bechoff et al., 2011). However, these technologies have not been widely implemented in the United States. Therefore, more research is needed to develop sustainable technologies for improving β-carotene retention in dried sweetpotatoes.

Canned sweetpotatoes are a classic value-added product, providing a use for smaller roots called “canners” and roots with visual defects. Peeled roots can be cut into any dimension or left whole and are typically canned with sugar syrup (Truong et al., 2018). The high-temperature thermal process and long cooling time can cause extensive softening, likely due to pectin breakdown (Truong et al., 1998). Canned sweetpotato firmness can be increased by a low-temperature blanch (62˚C) prior to canning to promote pectin methyl esterase activity and de-esterification of pectin (Walter et al., 2003) or by adding sugar and calcium to the canning solution (Bouwkamp, 1985).

Sweetpotatoes and its products have grown to be a notable market in the United States, worth around $600–700 million annually (USDA-NASS, 2023). Continued food science research in collaboration with breeding and agronomy efforts will be needed to sustain growth. This would include additional comprehensive consumer studies in US markets coupled with sensory profiling to develop targets for consumer-preferred sweetpotato cultivars; development of new technologies to bring additional value to off-grade sweetpotatoes; and identification of the chemical makeup that is

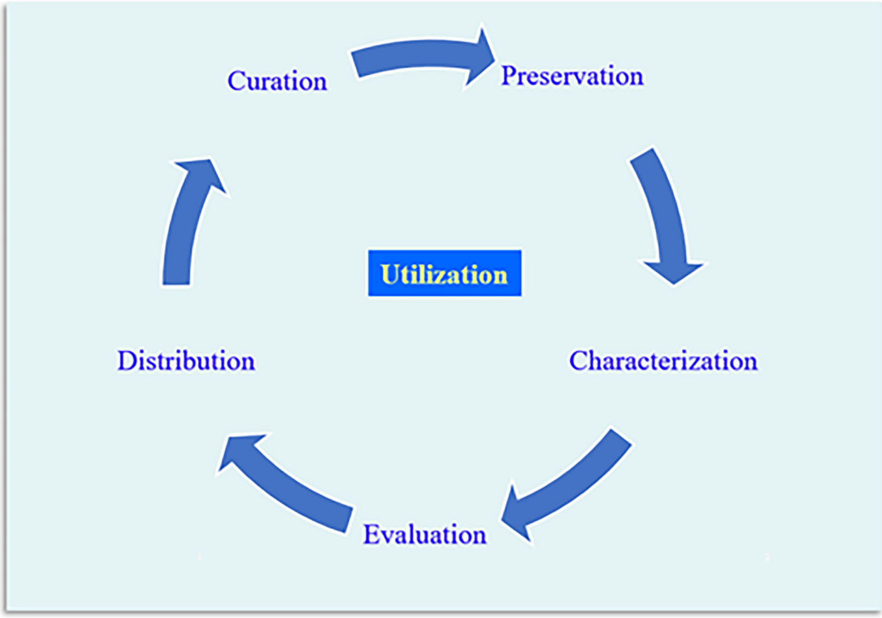

FIGURE 2 The components for the utilization of sweetpotato germplasm collections.

responsible for sweetpotato characteristics that are favorable for specific processed products.

2.5 | Sweetpotato germplasm collection

Sweetpotato germplasm collections contain natural variation, which provides the genetic base for cultivar development and improvement. The largest gene bank of sweetpotato is maintained at the International Potato Center (CIP) in Lima, Peru, which holds about 7000 accessions (6000 cultivated accessions and 1000 of its wild relatives) (Anglin et al., 2021). The USDA-ARS sweetpotato germplasm collection and its crop wild relatives are maintained at Griffin, GA, by the Plant Genetic Resources Conservation Unit. This collection contains 606 in vitro clonal accessions and 461 accessions of wild *Ipomoea* species maintained as seeds.

There are five major components for any plant germplasm collection that are interconnected, but the final purpose is utilization (Figure 2). The highly efficient and maximized utilization of the germplasm collection depends on how to carry out the tasks of all these five components.

Curation: The number of accessions in each gene bank is essential, but its number may not reflect its uniqueness. The passport data (a basic description of an accession) show redundant accessions from free exchanges that should be identified. After identifying redundant accessions, sweetpotato scientists can focus on investigating the unique accessions for their specific purpose. For any gene bank, there are still genetic gaps (i.e., existing genetic materials not being collected yet). More accessions should be collected based on geographic information and country origins to expand genetic diversity if possible.

Preservation: Compared with other species, the sweetpotato germplasm accessions are preserved (or maintained) as clonal materials instead of seeds. Currently, two big challenges exist for using traditional tissue culture to maintain sweetpotato germplasm. Because tissue cultures must be subcultured every 3–4 months to preserve cultures, the high frequency of propagation events can introduce both pathogen (bacteria, fungi, and virus) infection and somatic mutations. To prevent losing clonal accessions, cryopreservation methods provide a highly efficient long-term maintenance of sweetpotato germplasm (Park & Kim, 2015; Wilms et al., 2020).

Characterization: Characterization can cover many aspects, from morphological observation (such as a leaf, stem, root skin, and flesh color) to agronomical traits (such as growth rate and maturity) to responses for biotic (such as resistance to pathogen and pest) and abiotic (tolerance to drought and severe weather condition) stresses to chemical composition analysis (such as leaf and root macronutrient and micronutrients). Characterizing specific traits for research will focus on or utilize a subset of the germplasm collection. How this subset is selected will directly affect the characterization results. Using the core (representing 10% of the entire collection) or mini core (representing 1% of the entire collection) will be an efficient approach to characterize the germplasm collection for specific traits (Brown, 1989a, 1989b; Upadhyaya & Ortiz, 2001).

Evaluation: Sweetpotato breeding programs depend on the germplasm collection to improve nutritional quality,

TABLE 2 Distribution of sweetpotato accessions within the US states during 2020–2021.

State	Accessions
Alabama	12
California	45
Colorado	15
Georgia	15
Indiana	1
Louisiana	1
Maryland	1
Minnesota	2
North Carolina	1
Ohio	59
Oklahoma	5
South Carolina	258
Washington	17
West Virginia	1
Wyoming	2
Total accessions	435

disease/pest resistance, and other agronomic traits. To better utilize the sweetpotato germplasm collections, researchers have characterized the genetic diversity of global collections with various DNA marker platforms (AFLP, SLAF, GBSpoly, chSSR, and SSR) for 97 accessions from Tanzania (Elameen et al., 2008), 197 accessions from China (Su et al., 2017), 303 and 604 accessions from the United States (Slonecki et al., 2023; Wadl et al., 2018), 558 accessions from Korea (Lee at al., 2019), and 5979 accessions from CIP (Anglin et al., 2021). Based on the number of accessions investigated, two, three, four, and six subpopulations were revealed, respectively. High levels of redundancy were also uncovered. Some core collections had been established because none of these studies covered the world collection of sweetpotato germplasm, and DNA samples should be exchanged and collected to re-evaluate genetic diversity and population structure. The new core collection should be re-established using re-evaluation data for future utilization.

Distribution: In theory, sweetpotato germplasm accessions should be freely distributed or exchanged nationally and internationally if the request is eligible. There are some restrictions due to the germplasm distribution and exchange policy between states and countries. Even during the COVID-19 pandemic, Plant Genetic Resources Conservation Unit distributed many sweetpotato germplasm accessions to different states (Table 2) for breeding programs and genetic studies. There are two alarm signals that should always be kept in mind. One is not to distribute pathogen-infected accessions, and another is to control the invasive (threaten other plants) accessions within the restricted growing areas to prevent them from becoming out of control.

There are different limitations associated with the current germplasm collection. The genetic diversity and the chemical composition related to storage root quality are not well characterized, which needs further research. Also, the germplasm accessions undergo deterioration from somatic mutation over multiple generations and require long-term preservation techniques (such as cryopreservation) to maintain the germplasm collections. New cultivars and breeding lines need to be introduced to the collection to expand genetic diversity and selection choices for breeding programs.

3 | POLLINATION ECOLOGY AND THE FORAGING LANDSCAPE IN SWEETPOTATO ECOSYSTEMS

A significant portion of large-scale row crop agricultural systems is considered pollinator independent, as they do not require animal-mediated pollination services for the crop to set fruit. However, pollinators may still visit crops to collect resources. Bees are known to collect pollen from corn, nectar from cotton, and pollen and nectar from soybeans (Esquivel et al., 2021; Lin et al., 2022). These crops bloom after the spring resource flow, providing a valuable option for bees to obtain valuable nutrients, such as proteins and lipids in pollen and carbohydrates in nectar, while other resources are dwindling as temperatures increase. The presence of pollinators and their interactions with crops in these systems have been shown to provide benefits to crop yield, providing an opportunity for row-crop farmers and beekeepers to coexist with the shared interest of expanding their operations (Esquivel et al., 2021; Kral-Obrien et al., 2021). At the same time, landscape simplification and biotic homogenization have also altered the nutritional landscape available to bees (Hendrickx et al., 2007; Lau et al., 2023). With widespread pollinator population decline due to interacting stressors, which include habitat fragmentation and pesticide use, intentional management practices to promote flowering resources in large-scale agriculture to improve the overall ecosystem are critical for mitigating the stressors contributing to declining pollinator health (Crone & Grozinger, 2021; DeGrandi-Hoffman & Chen, 2015; Di Pasquale et al., 2013; Dolezal & Toth, 2018). This interaction is an opportunity to promote beneficial landscape for both pollinators and farmers to investigate the role of sweetpotatoes in the agroecosystem, an attractive resource for honey bees, bumble bees, and other solitary bees (Wolfe, 1992). In many cases, sweetpotatoes are planted along with other mass cropping systems, including soybeans, corn, and cotton, and can provide bees with valuable resources in a critical period of summer resource dearth (Dolezal et al., 2019; Lau et al., 2019).

Further research is needed to understand the plant–insect interactions between sweetpotatoes and bees to determine if sweetpotatoes can serve as a resource for bee nutrition. First, it is vital to compare bee diversity and bee health in locations where sweetpotato plots are present compared to sites on a similar row crop landscape without sweetpotatoes. This would provide information on the benefits of intercropping sweetpotatoes on pollinator communities. We can then expand on understanding the resource value sweetpotatoes add to the nutritional landscape for pollinators. Each plant species can produce pollen and/or nectar with a unique nutritional profile (Lau et al., 2022; Roulston & Cane, 2000). In many cases, a monofloral diet containing resources from a single species is suboptimal for bee health, as the diet can be deficient in a particular nutrient. Studies are required to understand the nutritional profiles of the pollen and nectar of sweetpotatoes, and whether sweetpotatoes can supplement the healthy landscape for pollinators. Also, metabolomics methods can be used to determine if the sweetpotato pollen metabolome is altered under drought stress. Since bees use floral volatiles as olfactory cues to find resources, the floral volatile organic compounds can be measured by using solid phase-microextraction (SPME) and analyzed using gas chromatography–mass spectrometry (GC–MS) (Rering et al., 2020; Silva et al., 2018).

Possibilities of using honey bees as an environmental biomonitor for early detection of sweetpotato pathogens need to be explored. Sweetpotatoes are plagued by various pathogens, including fungal diseases, bacterial diseases, viruses, and phytoplasma diseases (Hedge et al., 2012). Some of these diseases, such as the fungus causing stem rot, *Fusarium oxysporum*, have symptoms that are difficult to detect. Honey bees are the most important managed pollinator and can also be an informative biomonitor of plant diseases. Previous studies used front porch pollen traps to biomonitor pathogens found in sweetpotatoes (Cunningham et al., 2022; Tremblay et al., 2019). These traps are designed to knock off and collect the pollen pellet of a returning foraging bee. The pollen can then be sorted by color and texture to separate potential pollen collected from other sources and identified using traditional palynological techniques to morphologically identify pollen using morphological features and reference collections (Jones, 2014; Lau et al., 2019). Fresh nectar can also be collected during the sweetpotato flowering period. Both nectar and pollen can be analyzed for sweetpotato pathogens with targeted approaches, such as polymerase chain reaction (PCR) or enzyme-linked immunosorbent assay (ELISA) assays. Alternatively, high-throughput sequencing approaches can be used to detect and discover pathogens in sweetpotatoes.

Research and management considerations for various stakeholders need to be accounted. Farmers may not want to dedicate important land and resources to a cause that may not generate any profit. Supporting pollinator populations in a landscape can net positive returns for both beekeepers and farmers, as bees' pollination services improve crop yields in many different crops (Esquivel et al., 2021; Kral-O'Brein et al., 2021). Including sweetpotatoes in large row-crop systems can be a holistic approach with benefits to both farmers and beekeepers.

4 | PEST AND DISEASE MANAGEMENT IN SWEETPOTATO PRODUCTION

4.1 | Sweetpotato pests and IPM

US sweetpotato production in 2022 totaled 25.9 million hundredweight (cwt), an 11% reduction from 29.1 million cwt in 2021 and down 14% from 30.1 million cwt in 2020 (USDA-NASS, 2023). Sweetpotato farming on a smallholder scale has also diminished over the years in the sweetpotato-producing states in the southern United States. Higher labor costs, unavailability of desirable planting materials, and insecticide resistance associated with repeated applications of insecticides have all contributed to this reduced production. Furthermore, competition with large-scale production, high input costs, and low return have discouraged sweetpotato farming on smallholder scale that is 200 acres or less in production. The higher costs of insecticide applications also pose a further financial burden on resource-limited farmers and reduce profitability. The effects of climate change, such as higher temperatures, increased level of CO_2, and prolonged periods of drought, warrant investigation into the impact of both biotic and abiotic stress factors on the intensity of insect pests and diseases of sweetpotatoes and the crop yield (Quiroz et al., 2018). Research has shown that these biotic and abiotic stress factors affect the quality and yield of sweetpotatoes and leave them prone to insect pest and disease attacks (Imbo et al., 2016).

Several sweetpotato cultivars exist that are resistant to soil insects (wireworm) and foliar feeding insects (cucumber beetles, flea beetles). Unfortunately, they do not have the desirable agronomical traits (deep orange flesh color, wide adaptation, high yield) as the industry standard cultivars, Beauregard and Covington.

Numerous insect pests, mostly from the order Coleoptera attack sweetpotatoes in the United States (Cuthbert & Davis, 1970; Jackson & Bohac, 2006c; Jansson et al., 1990; Schalk et al., 1991; Sorensen, 2009). Most of these insects attack sweetpotato roots under the soil surface and they are well protected, rendering it difficult to control them with the available soil insecticides. Excessive infestations of sweetpotatoes by the foliar feeding insects indirectly reduce the plant yield, but can be easily controlled using foliar insecticides. Significant damage to sweetpotato roots is caused by immature or grub

TABLE 3 Common insect pests of sweetpotatoes in the United States and type of damage they cause to sweetpotatoes.

Insect species	Order/family	Common name	Type of damage
Conoderus vespertinus	Coleoptera/Elateridae	Tobacco wireworm	Storage roots
Conoderus bellus	Coleoptera/Elateridae	–	Storage roots
Conoderus falli	Coleoptera/Elateridae	Southern potato wireworm	Storage roots
Melanotus communis	Coleoptera/Elateridae	Corn wireworm	Storage roots
Phyllophaga ephilida	Coleoptera/Scarabaeidae	White grub	Storage roots
Euetheola humilis	Coleoptera/Scarabaeidae	Sugarcane beetle	Storage roots
Diabrotica balteata	Coleoptera/Chrysomelidae	Banded cucumber beetle	Storage roots/foliage
Diabrotica undecimpunctata	Coleoptera/Chrysomelidae	Spotted cucumber beetle	Storage roots/foliage
Chaetocnema confinis	Coleoptera/Chrysomelidae	Flea beetle	Storage roots/foliage
Chaetocnema denticulata	Coleoptera/Chrysomelidae	Toothed flea beetle	Storage roots/foliage
Systena frontalis	Coleoptera/Chrysomelidae	Red-headed flea beetle	Storage roots/foliage
Systena elongata	Coleoptera/Chrysomelidae	Elongate flea beetle	Storage roots/foliage
Cylas formicarius	Coleoptera/Brentidae	Sweetpotato weevil	Storage roots
Naupactus leucoloma	Coleoptera/Curculionidae	Whitefringed beetle	Foliage
Bemisia tabaci	Hemiptera/Aleyrodidae	Sweetpotato whitefly	Foliage
Aphis gossypii	Hemiptera/Aphididae	Cotton aphid	Foliage
Spodoptera frugiperda	Lepidoptera/Noctuidae	Fall armyworm	Foliage

stages of several species of soil insects (Table 3) (Reed et al., 2009; Sorenson, 2009).

Here, we will discuss the management practices for three major pests that cause significant economic damage to sweetpotatoes.

4.1.1 | Wireworms

Wireworms, the larvae of click beetles (*Conoderus* spp.), are highly polyphagous with a wide host range consisting of vegetables, grains, and other crops such as peanuts, strawberries, tobacco, and so forth. They are capable of inflicting economic damage to the roots and tubers due to their long life cycle and belowground protected habitat. In southeastern US states, *Conoderus* spp. are considered major insect pests (Rashid et al., 2010; Reed et al., 2009; Willis et al., 2010). The estimation of wireworm population by soil core sampling or soil bait sampling methods is complex and due to their cryptic life cycle, chemical control efforts are usually unsuccessful (Parker & Howard, 2001; Toth, 2013). Numerous studies on chemical ecology of different species of click beetles have been done in European countries and Japan (Toth, 2013; Toth et al., 2008, 2014). No current information is available about the chemical ecology of the *Conoderus* spp. Therefore, identifying any semiochemicals from this genus of click beetles and/or their host plants will provide first-hand information on their chemical communication. This can lead to the development of pheromone traps, which can play an essential role among risk assessment techniques available for sampling this pest. Identifying a pheromone will provide base information on their chemical ecology and a reliable method to detect when adults move into the area so that the management practices can be applied more effectively.

4.1.2 | Sweetpotato weevil

The sweetpotato weevil (*Cylas formicarius* F.) (Coleoptera: Brentidae) is considered the most severe pest of sweetpotatoes in the field and in storage. Throughout their life cycle, these weevils can cause feeding damage to sweetpotato roots, stems, and leaves. Females lay eggs by creating holes inside the sweetpotato roots. Excessive damage to the roots occurs due to the tunneling larvae, making them unacceptable for consumption. Even low numbers of larvae reduce sweetpotato quality and marketable yield. The larval development time is highly variable ranging from 12 to 154 days; therefore, even at low densities, the weevil can greatly reduce the marketable yield of sweetpotatoes (Sutherland, 1986). Pupation occurs within the sweetpotato and lasts for 5–11 days. The reproduction process is completed in the stems and the roots. Sweetpotato weevils are found throughout the southern US states from North Carolina to Texas and in the tropical regions worldwide. In Mississippi, the area north of interstate 20 has been declared weevil-free zone (Mississippi Department of Agriculture and Commerce, 2022), whereas the southern part of the state is in sweetpotato weevil quarantine zone. The sweetpotatoes grown in the south cannot be shipped to weevil-free areas in the northern states, which constitute major market for sweetpotatoes.

A heavy infestation of weevils can turn the vines yellowish, which is considered as a symptom of weevil infestation (Jansson & Raman, 1991; Kuriwada et al., 2013). De-vining at harvest is essential to keep the weevil populations low for the next season. Sweetpotatoes should never be left in the field unharvested. Weevils may also survive the winter in the stored storage roots that will be used as seed stock for the following season's planting. Application of Malathion can kill the over-wintering weevils in seed storage areas. A 5% Imidan dust application on sweetpotato roots before storage can provide effective control of weevils (Hammond et al., 2003). Good agricultural practices should be used such as planting certified clean seeds (virus and weevil-free), crop rotation, and burning crop residues.

Synthetic pheromones of sweetpotato weevil [(Z)-3-dodecen-1-ol (E)-2-butenoate] have been isolated and used widely for weevil monitoring under field conditions (Jackson & Bohac, 2006b; Reddy et al., 2012b; Sureda et al., 2006). Recent studies have also reported that sex pheromone-baited plastic pole traps caught 60%–78% more weevils than sex pheromone-baited delta traps, wing traps, or unitraps (Dilipkumar et al., 2019). Successful eradication of these weevils has been reported using a combination of male annihilation techniques and sterile insect technique in Kume Island, Japan (Himuro et al., 2022). Use of male annihilation techniques reduced the wild population density in a few years, followed by the release of millions of sterile weevils, which helped to completely eradicate the weevils from Kume Island. Use of pheromones and other semiochemicals will be highly beneficial in monitoring and management of these weevils in newly infested locations.

4.1.3 | Plant parasitic nematodes

Plant parasitic nematodes (PPNs) are ubiquitous in soils around the world, infecting nearly every cultivated crop on earth, and are estimated to cause $157 billion in yield losses annually (Abad et al., 2008). As a root crop, sweetpotato is particularly susceptible to quality issues that may result from PPN infections. Though dozens of PPN genera have been reported to be associated with sweetpotato, two genera, root-knot nematodes (*Meloidogyne* spp.) and the reniform nematode (RN; *Rotolyculus reniformis*), are the most prevalent and yield limiting on sweetpotato in the United States and many other regions around the world (Karuri et.al., 2017; Scurrah et al., 2005).

Root knot-nematodes (RKNs) affect a wide range of vegetables, row crops, and perennial plants (Nyczepir & Thomas, 2009). Even low levels of RKNs in the soil can reduce crop yield and the quality of roots (Karssen et al., 2013), and RKNs are found in nearly all areas where sweetpotatoes are grown (Clark et al., 2013; Stirling et al., 2020). Aboveground symptoms of RKN infection are nonspecific: chlorosis, necrosis, plant stunting, or wilting as the plant is under duress. The distinguishing symptoms of RKN damage are underground, where the roots have been infected and galled (Figure 3) (Karssen et al., 2013). The nematodes invade the plant and complete their life cycle within the storage root, leading to misshaped sweetpotatoes with galling and lesions on the surface. In some instances of infection, cracking of the storage root can also occur (Clark et al., 2013; Quesada-Ocampo, 2018).

FIGURE 3 Root-knot nematode (RKN, *Meloidogyne enterolobii*) infected sweetpotato cultivar Beauregard. In addition to reducing sweetpotato yield, this type of severe galling caused by high populations of RKN in the soil can also render storage roots unmarketable.

Historically, three closely related RKN species have caused the most yield losses in the tropical and subtropical environments where sweetpotato is grown: *Meloidogyne incognita*, *Meloidogyne javanica*, and *Meloidogyne arenaria*. More recently, a new RKN species, *Meloidogyne enterolobii*, has emerged as a severe pest due to its extensive host range, high level of virulence, and capability to overcome traditional RKN-resistant genes in a wide array of agricultural crops (Brito et al., 2020; Philbrick et al., 2020) (Figure 3). First reported in the continental United States in Florida in 2002, *M. enterolobii* has since spread to North Carolina, South Carolina, Louisiana, and Georgia (Rutter et al., 2019; Ye et al., 2013). This nematode is suspected to be spread by the shipment of infected seed roots used to plant crop fields annually (Quesada-Ocampo, 2018, 2019; Silva et al., 2021). Popular RKN-resistant sweetpotato cultivars used to manage endemic species of RKN have been shown to be ineffective against *M. enterolobii* (Rutter et al., 2019). The quick spread of this invasive RKN species has prompted significant concerns among growers and regulators, leading to the imposition of multiple interstate quarantines on sweetpotato seed roots (FINDMe, 2022; Hare, 2019). Distinguishing between *M. enterolobii* and the endemic RKN species requires a molecular test conducted by a trained pathologist, and growers should consult their state extension agents if they suspect they have a problem with any RKN.

It can be difficult for a grower to manage RKN, once a field has become infected. Various factors, including soil composition, temperature, average rainfall, and host crop rotations, can influence RKN population densities. RKNs adapt to many host plants and environments and can continue to reproduce successfully even as host plants are rotated across crop-growing seasons (Castagnone-Sereno et al., 2013). Though rotations to specific nonhost cover crops such as sunn hemp can significantly reduce RKN populations, they can quickly rebound once a highly susceptible host is replanted. Some popular sweetpotato cultivars, such as Covington, offer moderate resistance to the endemic RKN species and can help keep populations down. However, these same RKN-resistant cultivars are highly susceptible to *M. enterolobii*. Multiple resistant germplasms have been reported in the USDA-GRIN collection (Rutter et al., 2021; Schwarz et al., 2021). However, no *M. enterolobii*-resistant cultivars have yet been released for the commercial market in the United States.

With minimal management options currently available to control *M. enterolobii* in sweetpotato, the best option for growers is to prevent infection and spread of this nematode in their fields. The best way to prevent infection by *M. enterolobii* is to use clean "seed" material for planting that has been certified by a state agency (FINDMe, 2022; North Carolina Sweetpotato Commission, 2022). Though certified clean seed is more expensive, it is grown directly as either first- or second-generation material out of sterile tissue culture. It has been grown in fields that are monitored for the presence of *M. enterolobii* and other sweetpotato pathogens. Though noncertified roots may look unblemished, they may still harbor low levels of RKN and other pathogens that can permanently infest a field.

RN (*R. reniformis*) is another species of PPN that causes severe yield and quality issues in sweetpotato. It is the second most damaging PPN of sweetpotato in the southern United States (Abel et al., 2007; Smith et al., 2017). RN greatly reduces storage roots' quantity, size, and quality upon infection. Heavily infested sweetpotato storage roots are more likely to crack, and yield reductions have been noted to occur without cracking (Smith et al., 2017). Beyond parasitic females on the root itself, RN lacks any specific root symptomology, and foliar symptoms often resemble nutrient deficiency or water stress (Smith et al., 2017). This lack of distinctive symptoms has likely led to extensive misdiagnosis of RN infection.

Management tools for RN in sweetpotato are limited. Crop rotation is not as effective for this nematode because of its ability to persist in soil for up to 20 years in the absence of a suitable host and its ability to quickly rebound to a damaging level when a susceptible host becomes available (Khanal et al., 2018; Smith et al., 2017). A few fumigant nematicides can suppress RN populations, but the added cost of these nematicides and their adverse effects on health and the environment make them a poor option. The use of host plant resistance is the most economical approach to managing nematodes in the field. However, there are currently no RN-resistant sweetpotato cultivars available in the United States. As with any nematode problem, growers should sample their fields at the end of the growing season, preferably right before harvest, and send them to a state lab for quantification. Nematode soil counts can provide growers with valuable information on whether nematicide use is justified in the following growing season. And just as with RKN, using certified clean seed can also reduce the possibility of new fields becoming infested with this nematode.

4.2 | Host plant resistance in sweetpotatoes to ground-dwelling insect pests

Host plant resistance to most sweetpotato insect pests has been identified (Jackson & Bohac, 2006a, 2006b; Jackson et al., 2002, 2010, 2012; Wadl et al., 2022). In general, resistance to insects is not associated with undesirable traits in sweetpotato (Jones & Cuthbert, 1973), except for a reduction in final yield (Jackson et al., 2002). A long-term breeding program at the USDA-ARS, United States Vegetable Laboratory, has developed orange-fleshed sweetpotatoes for the primary domestic market and dry-fleshed sweetpotatoes for use in value-added products (processing). The program has been successful in creating high-quality orange-fleshed (Bohac et al., 2007; Collins et al., 1991; Jackson et al., 2010; Jones et al., 1986) and dry-fleshed (Bohac et al., 2001; Jackson et al., 2011) breeding lines and cultivars with resistance to the common ground-dwelling insect pests of sweetpotato.

Although cultivars and germplasm lines with high levels of multiple resistance have been released, these insect-resistant sweetpotato releases have not achieved commercial appeal due to their low yield, insufficient short maturity, and lack of disease resistance attributes. Research indicates ample phenotypic (Jackson et al., 2018, 2019, 2020; Wadl et al., 2022) and genotypic (Slonecki et al., 2023; Wadl et al., 2018) diversity within the USDA sweetpotato germplasm collections. This diversity, coupled with the existing sources of insect resistance, provides a foundation for the continuation of progress in developing improved sweetpotato with resistance to ground-dwelling insect pests. Furthermore, host plant resistance in sweetpotato offers an environmentally friendly IPM approach that can reduce the impact of pesticides, which can be expensive, unreliable, and toxic.

4.3 | Sweetpotato diseases and virus complex affecting sweetpotatoes

Sweetpotato is subject to many diseases caused by bacteria, fungi, and viruses. In general, bacterial diseases do not impact sweetpotato production. Many fungal diseases can infect the sweetpotato crop in different developmental stages. Major diseases on plant bed are Sclerotial blight (*Sclerotium rolfsii*), Slime molds (*Fuligo violacea* or *Physarum plumbeum*), and Rhizoctonia stem canker (*Rhizoctonia solani*). Many serious fungal diseases occur in field production of sweetpotato, including black rot (*Ceratocystis fimbriata*), foot rot (*Plenodomus destruens*), Fusarium root rot and stem canker and surface rot (*Fusarium oxysporum*, *Fusarium solani*), Fusarium wilt (*Fusarium oxysporum* f. sp. *batatas*), and Scurf (*Monilochaetes infuscans*). Vast majority of storage rot of sweetpotato is caused by fungi, including Rhizopus soft rot (*Rhizopus stolonifer*), Java black rot (*Diplodia gossypina*), dry rot (*Diaporthe phaseolorum*), punky rot (*Trichoderma koningii*), Alternaria rot (*Alternaria* spp.), blue mold rot (*Penicillium* spp.), and gray mold rot (*Botrytis cinerea*).

The most challenging diseases of sweetpotato are those caused by viruses due to vegetative propagation. Vegetative propagation may lead to accumulation of pathogens, particularly viruses, in the planting stock, resulting in decline in yield and sometimes quality of the crop (Clark et al., 2012). The lack of readily available virus-free planting material has remained a major limiting factor to sweetpotato production worldwide. Viruses are considered the second most important limiting factor (after weevils) to sweetpotato production.

Detailed studies have determined the incidence and distribution of sweetpotato viruses in several countries (Abad et al., 2007; Kwak et al., 2007; Mbewe et al., 2021; Sivaprasad & Gubba, 2013). According to Clark et al. (2012), the identified viruses have been assigned to nine families as follows: *Bromoviridae* (1 virus), *Bunyaviridae* (1), *Caulimoviridae* (3), *Closteroviridae* (1), *Comoviridae* (1), *Flexiviridae* (1), *Geminiviridae* (15), *Luteoviridae* (1), and *Potyviridae* (9) (Table 4). Both aphids and whiteflies transmit majority of the viruses in sweetpotato. Several studies have confirmed that weed species play a role in the epidemiology of some sweetpotato viruses (Akel et al., 2010; Tugume et al., 2010).

A common virus is the aphid-transmitted sweetpotato feathery mottle virus (SPFMV; *Potyvirus*, *Potyviridae*) (Syller, 2014). SPFMV causes transient symptoms when infecting alone; it is most damaging in mixed infections when it is synergized by co-infection with whitefly transmitted, phloem-limited sweetpotato chlorotic stunt virus (SPCSV) (Gibson & Kreuze, 2015). The synergistic interaction generally causes severe "sweetpotato virus disease" (SPVD; Gubba & Sivaprasad, 2015; Byamukama et al., 2004; Gibson et al., 1998), which is considered the most devastating viral disease worldwide. However, other virus combinations may cause symptoms that resemble SPVD. Depending on where sweetpotato is grown, different virus complexes have been identified to infect the crop (Clark et al., 2012). In temperate regions, the crop is generally affected by a complex of potyviruses and possibly other unknown viruses that typically cause yield reductions of about 20%–40% (Clark & Hoy, 2006; Clark et al., 2010). In East Africa, SPVD can cause 80%–90% losses in many high-yielding genotypes (Karyeija et al., 1998). SPCSV, on the other hand, is the most damaging virus causing permanent symptoms even when infecting alone. In some cases, SPVD can cause yield reductions of up to 98% (Mukasa et al., 2003).

With the adoption of molecular methods for virus research in the last two decades, there is a better understanding on the composition of sweetpotato virus complexes, the effects of virus diseases on production systems, the biology of the virus–plant interaction, and the management approaches of viral diseases. Since the initial identification of the sweetpotato leaf curl virus (SPLCV) (Lotrakul & Valverde, 1999; Lotrakul et al., 1998), a high genetic diversity of various begomoviruses has been identified on sweetpotato (Zhang & Ling, 2011). These emerging begomoviruses have caused severe yield losses of up to 60% compared to those of virus-free materials (Ling et al., 2010). With no virus-resistant cultivars available, planting virus-free materials is crucial to ensure sweetpotato production. Due to the importance of numerous viral disease problems, sweetpotato foundation "clean seed" programs were developed long before the advent of technology to produce virus-free propagating materials. In 2015, the National Clean Plant Network (NCPN) for sweetpotato was established under the umbrella of the United States Department of Agriculture (https://www.aphis.usda.gov/aphis/ourfocus/planthealth/ppa-ppdmdpp/sa_ncpn). Currently, sweetpotato clean seed programs have been established in California, Louisiana, North Carolina, Mississippi, Arkansas, and Hawaii (https://ucanr.edu/sites/ncpnsweetpotato). They apply the meristem shoot tip culture technique to generate virus-free materials for local cultivars (Alconero et al., 1975).

Meristem-tip culture starts with the excision of the shoot's organized apex from a selected donor plant for subsequent in vitro culture. The excised meristem tip is typically small (often <1 mm in length), which holds the potential to exclude pathogenic organisms that may have been present in the donor plants. Thermotherapy is commonly carried out at intervals of every 6 h, alternating between temperatures of 31 and 36°C, for 3–4 weeks before meristem-tip culture. This process is repeated and applied to the tissue-cultured plantlets to partially deactivate the viruses and slow down their movement. The ability to produce and maintain plants free of detectable viruses through meristem-tip culture has dramatically improved sweetpotato yields for several decades. However, as viruses can accumulate and transfer from one

TABLE 4 Important sweetpotato viruses and their mode of transmission.

Family	Genus	Virus species	Transmission/vector
Bromoviridae	*Cucumovirus*	Cucumber mosaic virus	Aphid
Bunyaviridae	*Phlebovirus*	Sweetpotato C-3 virus	Unknown
Caulimoviridae	*Badnavirus*	Sweetpotato pakakuy virus	Unknown
Closteroviridae	*Crinivirus*	Sweetpotato chlorotic stunt virus	Whitefly
Comoviridae	*Nepovirus*	Sweetpotato ringspot virus	Nematode
Flexiviridae	*Carlavirus*	Sweetpotato chlorotic fleck virus	Unknown
Geminiviridae	*Begomovirus*	Sweetpotato leaf curl virus and 14 other sweetpotato viruses	Whitefly
Luteoviridae	*Polerovirus*	Sweetpotato leaf speckling virus	Aphid
Potyviridae	*Potyvirus*	Sweetpotato feathery mottle virus; sweetpotato virus C; sweetpotato virus 2; sweetpotato virus G	Aphid
	Ipomovirus	Sweetpotato mild mottle virus; sweetpotato yellow dwarf virus	Unknown

generation to the next through infected vegetatively propagated materials (also known as "seeds"), studies indicate that a significant reduction of yield and quality may occur due to re-introduction of viruses from previous propagating materials. In two separate studies, 100% of virus-indexed plants were re-infected by SPFMV within the first year in the field, and a decline in yield occurred gradually over several years (Bryan et al., 2003). Therefore, sweetpotato "seeds," the primary method to reduce the damage of virus infections, are very expensive because farmers must regularly purchase virus-tested "seeds" due to the high re-infection rates in the field.

Factors such as virus variation, time, and required expenditure have mired conventional breeding efforts (Lomonossoff, 1995). Moreover, genetic sources of resistance are scarce and the incorporation of such resistance from the wild diploid *Ipomoea* spp. species into polyploid sweetpotato is a complicated task. With the development of genetic transformation systems, genome sequences, and genetic engineering tools, for example, CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats)/Cas9, molecular breeding provides a promising strategy for the development of novel cultivars with value-added traits. The CRISPR/Cas9 system works to induce targeted genetic modifications to regulate endogenous gene expression, and the "transgene-free" end products set it apart from traditional genetically modified organisms (GMO) where foreign gene(s) are integrated into the host genome (Chaudhary et al., 2018). The CRISPR/Cas9 system has ushered in the beginning of a new era in basic and applied biological sciences (Bomgardner, 2017; Reis et al., 2014). By using the CRISPR-Cas13 technique, a recent study demonstrated sweetpotato lines with enhanced viral disease (SPVD) resistance by targeting one of its essential pathogeneses-related factors (i.e., SPCSV-RNase3) (Yu et al., 2022).

The solution to the problems caused by sweetpotato viruses is to ensure that growers plant virus-indexed clean propagation material or "seeds." However, by estimate, there is a 72% shortfall of clean plant units needed to cover all sweetpotato acreage (NCPN Network News, May 2018). Thus, there is a considerable demand for establishing certified nursery farms to produce clean "seeds" in the sweetpotato industry. Besides, the high reinfection rate of viruses in production requires the farmers to frequently purchase virus-indexed propagation material, which significantly increases their financial input for propagation and production. Therefore, using other biotechnological approaches, such as gene transformation or genome editing techniques, to produce virus-resistant cultivars would be another promising strategy to control the virus in sweetpotato.

5 | WEED MANAGEMENT IN SWEETPOTATO PRODUCTION

Weed management is consistently ranked among the top research priorities of the US sweetpotato industry. *Amaranthus* species can reduce yields up to 85% in sweetpotato (Basinger et al., 2019; Smith et al., 2020). Yellow and purple nutsedge (*Cyperus esculentus* L. and *Cyperus rotundus* L., respectively, Family: Cyperaceae) negatively affect sweetpotato yield and quality, and losses from 18% to 96% have been reported (Meyers & Shankle, 2015). Large crabgrass [*Digitaria sanguinalis* (L.) Scop.] at densities of 1–16 plants·m^{-1} of row reduced yields from 35% to 76% in sweetpotato (Basinger et al., 2019). Grieg and Al-Tikriti (1966) and Glaze et al. (1981) found that yields of sweetpotato plots were reduced by over 90% in comparison with treatment plots receiving herbicides, hand weeding, and cultivation. Glaze et al. (1981) reported that Georgia Red sweetpotato yields were reduced by 90% when weedy control plots were compared to plots receiving cultivation and herbicides in 1 year of the study.

Conventional sweetpotato growers utilize herbicides, between-row cultivation, mowing, and hand removal to manage weeds. Currently, 10 herbicides are registered for weed control. Those commonly used are flumioxazin, *S*-metolachlor, clomazone, and two graminicides (sethoxydim and clethodim). Although napropamide and DCPA are registered for sweetpotato, they provide inconsistent and often inadequate weed control (Weir, 2001). Each of the registered herbicides has drawbacks. Flumioxazin, *S*-metolachlor, and clomazone require rainfall or irrigation for activation, but few producers have the infrastructure for overhead irrigation. If rainfall is not timely, weeds emerge before activation and are not controlled. Flumioxazin must be applied before transplanting and requires that planting ridges be formed and then the top of the ridge leveled. If not done correctly, the herbicide is removed from the center of the planted row during transplanting, thereby providing little weed control. Weeds that escape control in the row cannot be controlled with cultivation and compete with the developing crop.

In organic and/or resource-limited production systems, weed management is more difficult because the use of synthetic herbicides is prohibited or too expensive. Mechanical weed control is a common practice among these sweetpotato producers, who disc multiple times during field preparation and cultivate two to three times during the growing season. Escaped weeds are removed by hand. Many organic fields in the Southeastern United States are hand weeded at an estimated expense of $510 per acre. The lack of adequate weed control is the most critical obstacle to adopting organic production or sustainable cultural practices (i.e., no tillage or minimum tillage). Crop rotation to manage weeds can be successful if the crops are more competitive with the target weed species and a minimum of 2 years is often required to significantly reduce weed pressure before planting sweetpotato again (Monks et al., 2018).

Cultivars tolerant to weed interference can be essential components in integrated weed management in both conventional and organic production. The leading US sweetpotato cultivars (Beauregard and Covington) are highly susceptible to weed interference to the extent that total crop failure has been reported (Meyers et al., 2010). Delaying weeding beyond 2 weeks after planting resulted in substantial reduction in yield (Levett, 1992; Seem et al., 2003). Yields of Carolina Bunch, a cultivar with semi-erect vine growth habit (Huamán, 1991), were reduced by ≤20% by weed interference in comparison to weed-free plots, whereas all other clones were reduced from 50% and 70% (La Bonte et al., 1999). Sweetpotatoes with erect to semi-erect growth have shorter internodes, which results in a denser canopy with greater height and more significant branching in the early growth stages. These clones with erect to semi-erect plant habit grow radially and form a closed canopy earlier than cultivars with a prostrate spreading plant habit, thus improving weed suppression. Harrison and Jackson (2011) compared Carolina Bunch and Beauregard (spreading habit) in weed-free plots and reported yield reduction in Beauregard. Development of erect and semi-erect vined sweetpotato germplasm could allow increased tillage later into the season as the vines would not wholly cover between the rows. To provide additional weed and insect management strategies for sweetpotato, research is required for the development of insect-resistant germplasm that also has competitive weed tolerance potential by breeding and selecting for sweetpotato clones that are fast growing and have semi-erect to erect canopy architecture.

Research studies have reported that some cultivars may be more tolerant to weeds than others (Jackson et al., 2011; La Bonte et al., 1999). A study at United States Vegetable Laboratory compared the performance of six advanced sweetpotato clones to three control cultivars (Beauregard, Covington, and Monaco) over two seasons under various weed-free intervals and highlight the potential for the development of germplasm with tolerance to weed interference and resistance to insect pests (Wadl et al., 2022). Additional research is needed to address the need for multi-year field trials for evaluating insect resistance, lack of existing germplasm with erect plant habit, lack of sufficient weed pressure each year, and impact of abiotic stress (drought and flood) on yield.

6 | WATER MANAGEMENT IN SWEETPOTATO PRODUCTION

Sweetpotato is considered a drought-tolerant crop (Khan & Doty, 2009) but also sensitive to water logging (Gomes & Carr, 2003a). As such, water plays a vital role in its growth and yield. Little is known about the water requirements and yield responses of this crop to irrigation. Norman and Molales (1984) and Gomes and Carr (2003a) commented on how few studies there have been on the water use (WU) of this crop despite its many cultivars. Most of the water research in sweetpotato has been on the effects of water deficit as most of this crop is produced in areas that are primarily rain fed, such as the drought-prone tropics. Some cultivars have been shown to be susceptible to drought (Adebola & Abe, 2013; Karakas et al., 2021). Water deficits reduce leaf water potential and total WU, and subsequently reduce stomatal conductance, leaf area, root mass, total plant mass, and tuber yield (Sivan et al., 1996). Van Heerden and Laurie (2008) examined the effects of long-term restricted water supply on shoot development, photosynthesis, and storage root yield of two cultivars in rainout shelter conditions in South Africa and found that significant decreases in stomatal conductance occurred in both cultivars after 5 weeks of treatment.

However, continued measurements revealed a significant cultivar difference in the persistence of this response and its effects on CO_2 assimilation (Van Heerden & Laurie, 2008). Ekanayake and Collins (2004) found that drought stress significantly reduced nitrogenous compounds and root yield of sweetpotato in Peru. In Thailand, Yooyongwech et al. (2017) were able to elevate water-deficit tolerance by using a foliar application of paclobutrazol that improved soluble sugar and free proline accumulation, photosynthetic pigment stabilization, photosynthetic abilities, growth performance, and storage root yield.

Several studies have shown contradicting information about the necessity of irrigation in sweetpotato. Smittle et al. (1990) showed that marketable yield and yield of US No.1 grade roots generally decreased when soil water tensions exceeded 25 kPa before irrigation, while soil water stress of 100 kPa during storage root development did not significantly affect yield in a field study in Georgia. Lana and Peterson (1956) showed similar results with peak yield when irrigated at 50% available soil moisture. However, in other studies (Bowers et al., 1956; Ghuman & Lal, 1983), the yield was increased in irrigation plots compared with nonirrigated plots, but there was no difference among the different irrigation frequency and quantity levels examined. Hernandez (1965) also recommended that the amount of water needed to produce a good crop varies yearly and that irrigation should commence while the soil moisture in the root zone is higher than 25%, possibly 40%–50%. It is often anecdotally recommended that irrigation is only needed in the early planting stages (first 30 days), though there is little information available in the literature to indicate ideal timings and methods of irrigation.

Very little research has been done on WU (the amount of water used to produce crops in the field) and water-use efficiency (WUE; the amount of water used in relation to yield) in sweetpotato, and field studies are minimal in general, especially in the United States. Kelm et al. (2001) conducted pot-scale research on the effect of nitrogen deficiency on the WUE of one Peru cultivar. They showed WUE was dependent on leaf inclination and chlorophyll content in leaves, which, in turn, was dependent on nitrogen supply. In 2014, Masango (2014) published a master's thesis on WUE in orange-fleshed sweetpotato in South Africa under rain shelters with different irrigation regimes and stated WU ranged from 298 to 478 mm. WUE ranged from 64.8 to 97.5 kg·ha^{-1}·mm^{-1}, while Afzal et al. (2021) put WU at 500 mm on average worldwide. Gomes and Carr (2003a) measured WU from well-watered crops as 800 mm during the rains and 550 mm during the dry season, while the WU for the rain-fed crops was 360 and 180 mm, respectively. Karakas et al. (2021) found that seasonal water consumption of two sweetpotato cultivars was calculated as 808 and 826 mm, under no water deficit in Turkey. Gomes and Carr (2003b) recorded WUEs of 13 kg·ha^{-1}·mm^{-1} in the rains and 24 kg·ha^{-1}·mm^{-1} in the dry season, indicating each unit of water "lost" in the dry season was nearly twice as productive as the same amount of water consumed by the crop in the rains. Dladla et al. (2018) examined the effect of ridge type and environmental conditions on WUE in South Africa and found that WUE was higher under peaked ridges. They also stated that cultivars performed differently at each site and under the different ridge types and suggested producers adopt different cultivars across different environments to improve yield and WUE. No numbers for sweetpotato WU or WUE were found for the United States from the last 30 years.

7 | IMPACT OF CLIMATE CHANGE ON GLOBAL SWEETPOTATO PRODUCTION

Global food security in the 21st century is severely threatened by climate change and may impact various agricultural production systems. It is estimated that climate change will have positive and negative impacts on agricultural systems globally, with adverse effects outweighing the positive ones (Bage, 2007). Climate shifts lengthen growing seasons, and rise in temperatures may bring along negative implications such as reduced precipitation, thus affecting water availability and, in turn, crop water requirements (Eitzinger & Kubu, 2009; Molua & Lambi, 2006). An increase in atmospheric temperature and elevation of CO_2 concentration could influence crop yield and may directly or indirectly impact crop pests, weeds, and diseases. Climate variability and change may have a more significant impact on tropical agricultural production systems where the temperature is projected to increase from 1.5°C in the next 20 years to 4.3°C by 2080 (Hepworth & Goulden, 2008), leading to changes in the distribution of agroecological zones, soil moisture, and shortened growing seasons (Hulme, 1996).

7.1 | Impact on pest and disease management

Climate change can impact pest and disease occurrences, host–pathogen interactions, ecology and distribution of insects, time of appearance, natural enemy populations, insect migration, and overwintering capacity, becoming a major setback to agricultural production (Ayyogari et al., 2014). As insects are poikilothermic organisms, the increase in atmospheric temperature may directly impact insect behavior, developmental biology, host selection, reproduction, population dynamics, and dispersal mechanisms. Indirectly, climate change may affect the plant–pest–natural enemy interactions and their relationships with other insect species, natural enemies, symbionts, and mutualists (Abdallah et al., 2014). These climatic factors create new ecological niches for insects to establish and spread in new geographical areas (FAO, 2019). Studies have reported how temperature changes affect the growth of pest populations in important grain crops such as wheat, rice, and maize. Deutsch et al. (2018) reported that global warming would accelerate the growth of pest populations in wheat grown under temperate conditions and decrease the growth of pest populations in rice grown in tropical zones. Maize grown in temperate and tropical regions may experience a mixed growth response of pests to global-warming-associated changes. Bale et al. (2002) predicted that aboveground insects would be more affected by increased temperatures than belowground insects. As sweetpotato roots are grown belowground, many root-damaging pests are belowground and may not be significantly affected by this temperature increase.

7.2 | Impact of CO_2 levels on sweetpotato production and yield

It is estimated that the CO_2 concentrations will increase from 400 to >700 ppm by the end of the century (Fahad et al., 2017). Elevated CO_2 has been shown to be beneficial for C3 plants such as potato, sweetpotato, and yam compared to C4 plants such as maize and sorghum whose yields especially for maize were significantly reduced (Raymundo et al., 2014). The effects of increasing CO_2 levels on insect pests are highly dependent on their host plants (Coviella & Trumble, 1999). These differential effects of elevated atmospheric CO_2 on C3 and C4 plants may result in asymmetric effects on herbivory, and the response of insects feeding on C4 plants may differ from that of C3 plants. C3 plants are likely to be positively affected by elevated CO_2 and negatively affected by insect response, whereas C4 plants are less responsive to elevated CO_2 and, therefore, less likely to be affected by changes in insect feeding behavior (Lincoln et al., 1986; Skendzic et al., 2021). Studies by Finnan et al. (2005) showed that potato yields increase with elevated CO_2 in open-top chambers (OTCs) and free air carbon dioxide enrichment (FACE) systems across Europe and the United States. Other studies indicated that increased temperature may counteract the positive effect of elevated CO_2 in potatoes (Schapendonk et al., 1995). Biswas et al. (1996) showed that sweetpotatoes under elevated CO_2 in combination with water stress did not respond to elevated CO_2, while the yield of well-watered plants increased significantly with elevated CO_2. This shows that multiple factors and interactions may play a role in determining yield parameters under varying climatic factors.

7.3 | Impact of precipitation patterns on sweetpotato production

Changes in precipitation patterns can also influence pest occurrence and development. Insect species that overwinter in the soil can be directly affected by heavy rainfall and flooding conditions (Skendzic et al., 2021). Wireworms are a damaging pest of storage root crops such as potatoes, sweetpotatoes, and sugar beets that are grown belowground. Staley et al. (2007) found rapid growth of wireworm populations in the upper part of the soil due to increased summer rainfall events as opposed to ambient and drought conditions. Yihdego et al. (2019) reported that drought-stressed plants are more susceptible to insect attack because of decrease in plant secondary metabolite production that contributes to plant defense responses.

Because tuber and root crops are a significant food source and a staple for many developing countries in Africa, many cropping models predicting climate change's impact on water and yield estimates for sweetpotatoes are studied and reported for sub-Saharan countries. Tuber crops are C3 plants, and their photosynthesis relies mainly on CO_2 concentration (Flexas & Medrano, 2002). If the crops' water needs are not met, the water deficit may lead to stomatal closure, thus reducing the amount of water lost through evapotranspiration (Blum, 2009). If the soil and plant water status are not replenished through irrigation, stomatal closure leads to reduced CO_2 uptake, which results in reduced biomass production. Under global warming conditions, an expected increase in temperature, evapotranspiration, and CO_2 may lead to a decrease in soil moisture affecting the soil–plant water relations (Kimball & Bernacchi, 2006). Under drought-like conditions, transpiration efficiency is vital in maximizing biomass production and the crops' primary productivity through increased CO_2 fixation (Gherardi & Sala, 2020). If these irrigation requirements during the root bulking stage (mid) of sweetpotatoes are not met, it may lead to reduced growth and development of tubers (Kassam & Smith, 2001).

While studies have combined climate, crop, and economic models to examine the impact of climate change on agricultural production and food security, results have varied widely due to differences in models, scenarios, and data used in these studies. Understanding the magnitude of the impacts of climatic factors on sweetpotato production is further complicated by the interaction of numerous biophysical and socioeconomic factors (Raymundo et al., 2014). Two crop simulation models, MADHURAM (Somasundaram & Santhosh Mithra, 2008) and SPOTCOMS, which is a MADHURAM model with a modified canopy algorithm (Santhosh Mithra & Somasundaram, 2008), have been reported for sweetpotatoes (Raymundo et al., 2014). The MADHURAM model simulates photosynthesis across canopy layers to calculate direct and diffused sunlight interception. This model considers three phenological stages (initial–middle–final), crop growth, and yield by considering water, potassium, and nitrogen limitations. Compared to MADHURAM, SPOTCOMS is a simpler model, although the canopy development includes branching (Santhosh Mithra &

Somasundaram, 2008). In both MADHURAM and SPOTCOMS, the phenology stages are determined by growing degree days, with a base temperature of 8˚C, an optimum temperature of 25˚C, and a maximum temperature of 38˚C. These values for base temperature appear low as sweetpotato is cropped in subtropical and tropical regions. No published studies have reported applications of these two sweetpotato models, except for Villordon et al. (2009), who used these models to simulate the harvest dates for sweetpotatoes in Louisiana.

Using CROPWAT 8.0 model, Mbayaki and Karuku (2021) predicted the implications of climate change on crop water requirements for the short rain seasons between 1991 and 2016 (baseline climate) and the future from 2020 to 2039 (climate change) in sweetpotato growing regions of Kenya. Based on the models, this study predicted that the average annual temperatures would rise by 36.3% and could shorten the sweetpotato growth periods by 42 days lowering the yield. Irrigation water requirements will be increased as the annual rainfall is supposed to reduce by 16.7%, which may impact soil moisture and reduce water availability. While Mbayaki and Karuku (2021) predicted a decrease in rainfall and a reduction in yield unless the irrigation requirements are not sufficiently met, Ddumba (2018) indicated a 50-mm increase in rainfall for most parts of Kenya and Tanzania, and a decrease in rainfall for central Uganda and regions of southern Tanzania using another SPOTCOM crop model. Based on these projections, a rise in rainfall will increase sweetpotato yield by 4 t·ha^{-1} in western and southern Kenya in 2050 and an overall increase by 1–3 t·ha^{-1} across the east African region. This model projected increased precipitation and temperature; therefore, higher sweetpotato yields of 7, 10, and >20 t·ha^{-1} were projected for the 2030s, 2050s, and 2070s for four cultivars grown in the east African regions. Though some of these models have contradicting findings on precipitation and yield projections of sweetpotatoes, these studies agree that the atmospheric temperature is going to rise globally and will have an impact on crop production.

Crop models can be used effectively to assess the impacts of climate change and potential adaptations if the models are well-tested and proven to reproduce the results from field-based experiments, including variations in climate change factors (Raymundo et al., 2014). Such crop models are lacking in tuber crops, and there is an urgent need to develop models that combine physiological studies on high temperature, heat stress, CO_2, and water stress, evaluating different cultivars and their impact on crop growth dynamics, pest and diseases, nutrient and water uptake, and yield. Collecting such detailed data on crop growth under varying field conditions and farming situations will help to develop better agronomic decisions locally, regionally, and globally.

8 | CURRENT LIMITATIONS AND CHALLENGES FOR SMALL-SCALE AND ORGANIC FARMERS

Currently, there is no detailed published information on the demographics, acreage, production practice problems, and challenges of underserved sweetpotato growers, especially African American growers. In this regard, the 1890 Small Farm Working Group is working to address the knowledge gap and to increase the adoption of new, practical, and economical IPM practices by underserved small farmers. The 1890 Small Farm IPM Working Group has informally surveyed and engaged with over 60 underserved farmers concerning priorities and challenges, such as climate-smart IPM and organic production practices via letters of support, personal engagement, and phone interviews. The main concerns for organic sweetpotato producers were identified as (1) labor cost required for organic production, (2) the efficacy of biopesticides in managing sweetpotato pests, and financial benefits, (3) limitations on having enough land for crop rotations or suitable rotational cash crop that will return an economic benefit, if not growing sweetpotatoes, and (4) input cost of organic production and markets for selling organic sweetpotatoes. Also, small and organic growers face challenges with inadequate number of marketplaces and proper agricultural infrastructures (i.e., fruit and vegetable processing facilities). Smallholder growers also require more technical assistance through research, extension, and educational programs related to organic pest management, water and nutrient management, and climate-smart agricultural practices. Financial management is another major limitation that limits access of smallholder farmers to capital, land, technology, labor, and experiential knowledge. There is a strong interest among underserved farmers to participate in and adopt organic production practices, developing markets and value-added products for sweetpotatoes.

8.1 | Small farm pest management challenges

Surveys on small-farm IPM challenges are scarce. Pinero and Keay (2018) conducted an online survey aimed at characterizing farming practices and challenges, methods of pest management, level of IPM knowledge, and preferred sources of IPM information of commercial fruit and vegetable producers in Missouri. This survey elicited responses from growers farming in 44 counties across the state and provided a comprehensive perspective on the scale and scope of production of fruit and vegetable crops. When asked to select the most significant challenge on their farm from among eight options, 43% of respondents selected plant pests (which comprised diseases, arthropods, and weeds) followed by weather (21%). Both conventional and organic producers chose insects as the most important pest of tree-fruit pests, followed by diseases. In vegetables, insects were chosen as the most significant problem, followed by weed management. Both groups selected diagnosing diseases as their most-significant challenge; however, conventional growers had more trouble with deciding which fungicide chemistries to use more often than developing a prevention plan. Over 56% of the farmers had concerns about disease management for transplants in greenhouses and nurseries. Both conventional (68%) and organic (70%) producers selected insects as a significant pest of vegetables. Both groups consider themselves as having a medium knowledge of IPM, possibly reflecting the need or requirements of certified organic growers to understand and implement plant health management strategies such as crop rotations, cover crops, sanitation, cultural practices, and biological controls as indicated by the USDA's National Organic Program final rule (USDA, 2000).

The authors of the small-farm IPM study in Missouri pointed out that their survey of small farmers was not ethnically diverse, with 94% of respondents describing themselves as White. This was followed by growers of Asian/Pacific Islander origin (8%) and Black or African American (3%). According to the 2012 Census of Agriculture (USDA-NASS, 2014), 99.4% of farms (all farm types) in Missouri were operated by Whites. In contrast, Hispanics operate only 0.8% of farms, and 0.28% were operated by either Black or African American growers. There is a need to survey and document IPM challenges and farming practices of diverse underserved small farmers. In other southern states, Black farmers constitute a larger share of total farmers, with Mississippi (12%) leading, followed by Louisiana (7%), South Carolina (7%), Alabama (6%), and Georgia (4%) (USDA-NASS, 2014). Also, more information is needed on pest management challenges and concerns of underserved smallholder farmers.

8.2 | Approaches and solutions for organic and underserved farmers

Specialty crop growers should adopt climate-smart practices such as no till, cover crops, biodiversity, and use of biologicals for establishing consumer-driven markets for climate-smart commodities. Alcorn State University (Lorman, Mississippi) is a collaborator on a research and educational project to facilitate the implementation of climate-smart production practices by underserved small-farm specialty crop growers (including sweetpotatoes). This project aims to develop robust tools for measuring inputs, outputs (climate-smart ecosystem services), and crop yields and to establish systems for traceability, verification, and marketing of climate-smart commodities. Growing sweetpotatoes using climate-smart agricultural production practices combined with marketing is a solution to help small, underserved farmers get premium prices for their produce.

In recent years, organic produce is in high demand and there is a long history and interest of African American farmers growing crops organically. However, the transition to organic production can be a lengthy and expensive process for many Black farmers. In the 2012 Census of Agriculture (USDA-NASS, 2014), out of the over 33,000 principal Black farmers, around 116 were certified organic farmers, which is less than 0.1% of total certified organic farmers (14,093) in the nation. Mississippi has the highest percentage of African American specialty crop farmers in the United States. Mississippi, and other states in the Southeast with significant numbers of Black specialty crop farmers (LA, AL, SC, and GA), is an important geographical area to focus on expanding organic sweetpotato production (Grist, 2016).

9 | CHALLENGES AND SUSTAINABLE APPROACHES FOR IMPROVING SWEETPOTATO PRODUCTION

Root/tuber crops such as sweetpotatoes have contributed significantly to reducing poverty in the developing world and have enhanced food security by addressing hunger, malnutrition, and micronutrient deficiency, thanks to their higher nutrient content (Afzal et al., 2021). In addition to being a staple food crop and animal feed, sweetpotatoes have potential for biofuel production due to its high starch content and bioethanol yield (Ziska et al., 2009). Sweetpotato cultivation also generates sustainable income for smallholder farmers and contributes to the livelihood of farmers due to lower production costs. Diversification of sweetpotato through processed products and value addition can generate extra income and increase crop utilization. Also, sweetpotato can increase resilience and reduce the vulnerability of smallholder agricultural production systems to climate change effects and other disruptions (Afzal et al., 2021). There is a wide genetic diversity of this crop that is maintained in gene banks for farmers (Anglin et al., 2021; Elameen et al., 2008; Lee et al., 2019; Slonecki et al., 2023; Su et al., 2017; Wadl et al., 2018). All these attributes associated with sweetpotato production make it a sustainable crop for agricultural production systems. However, there are many challenges related to sweetpotato production, such as climatic factors, pest and disease problems, value addition, nutritional quality, marketability, and cultivar selection that make this crop less attractive to some growers. Sustainable approaches need to be developed in different areas to attract more growers into this crop and increase the acreage, production, and value addition of this crop in the United States and globally.

9.1 | Exploring new germplasm collections, sweetpotato chemistries, and their health benefits

Consumer demand for purple sweetpotatoes has steadily increased over the last decade. There is more interest from growers for different cultivars, especially purple sweetpotato cultivars, but more research is needed for the development of cultivars and their utilization. Germplasm collections of different cultivars need to be re-evaluated for genetic diversity and population structure. To expand the genetic diversity of the collection, newly developed cultivars and advanced breeding lines need to be acquired, evaluated, and characterized for nutritional quality. Single-nucleotide polymorphism arrays can be effectively used for the evaluation of germplasm, and cryopreservation techniques can be employed for germplasm preservation and overcoming germplasm deterioration. Further analytical studies are required to study the effects of anthocyanin types and contents of purple sweetpotato cultivars and to identify compounds that have immunomodulatory effects. Technological advances in analytical chemistry are available to characterize the specific molecules in sweetpotatoes that contribute to specific health-promoting properties as well as sensory traits. For example, anthocyanin types and quantities can be characterized using liquid chromatography with photo diode array and triple quadrupole mass spectrometer detectors (LC–PDA–TQMS), and aroma compounds present in the baked roots can be characterized using comprehensive two-dimensional gas chromatography with a high-resolution mass spectrometer (GC×GC–ToFMS) and sensory analysis. Fractionation and purification of these compounds enable further testing in model cell lines to screen for compounds that are potentially health promoting. These approaches will help to identify favorable purple sweetpotato anthocyanins that have health-promoting properties and are beneficial or inconsequential to the sensory experience. Contrarily, anthocyanins that have minimal health benefits and/or are associated with undesirable sensory attributes will be targeted for reduction in purple sweetpotato breeding selections and production practices. This will also benefit health sciences, food sciences, and horticulture programs involved with anthocyanin-containing food products or crops that would like to decrease anthocyanins with undesirable tastes and increase those with beneficial attributes (e.g., natural color extracts, blueberry breeders).

Sweetpotatoes have great potential for value addition through food processing. However, processing sweetpotatoes has additional hurdles due to its unique composition and labile phytonutrients. Some of the US sweetpotato cultivars have a higher sugar content. Therefore, achieving a crispy texture in fried products (e.g., chips and fries) without excessive browning and acrylamide production is a challenge. Identification of sweetpotato attributes (e.g., chemical composition, starch attributes, and cell wall structures) that impact fried sweetpotato textures will aid breeders and processors in selecting cultivars and how to make the products that meet consumer preferences. Further research is needed to fully understand the impact of sweetpotato chemistry on product quality and enable the development and optimization of sweetpotato processing technologies. Improving our knowledge on sweetpotato chemistry and processing research will bring more value to the sweetpotato industry, including small- and large-scale farmers, processors, and consumers.

9.2 | Developing sweetpotato farms as a niche for conserving pollinators for multiple crops

In many cropping situations, sweetpotatoes are planted along with other mass-produced crops including soybeans, corn, and cotton. During flowering in the late summer, sweetpotatoes can provide bees with valuable resources in a critical period of summer when resources are scarce. Since sweetpotatoes blossom during this time, the resources offered by the flowers can be essential for bee populations in an environment. However, sweetpotatoes are propagated vegetatively and do not require pollination services for crop production, creating little incentive for a sweetpotato producer to actively maintain bee populations on their crop. Determining the value sweetpotatoes bring to pollinators, which can improve pollinator health and overall agricultural ecosystem productivity, can be a working point for developing shared interests between growers and beekeepers. If sweetpotato cultivars are used to help sustain pollinator populations, further research will be needed to determine the possibility and extent of pollinators acting as vectors for sweetpotato pathogens (Real et al., 2018). However, there can be advantages for incorporating pollinators, as honey bees can be used as a biomonitor for hard-to-detect plant diseases (Cunningham et al., 2022; Tremblay et al., 2019).

Floral resource nutrient profiles for sweetpotatoes need to be established alongside other plants to strategically build a landscape suitable for both growers and pollinators. The diversity and health of different pollinators in sweetpotatoes are not well understood and need to be compared with similar crop landscapes without sweetpotatoes. These pollinators include wild bees, which can be assessed for abundance and diversity using passive and active sampling techniques. Using blue vane traps and yellow pan traps, the diversity of bees and other insects in the sweetpotato landscape can be sampled to get more information on pollinators. From the grower's perspective, honeybees are the most important managed pollinator and can also be an informative biomonitor of sweetpotato diseases. Nectar and pollen collected using front porch pollen traps can be analyzed for sweetpotato pathogens with targeted approaches, such as PCR or ELISA assays.

9.3 | Novel pest management tools and disease detection methods

Higher costs associated with insecticidal applications for pest management pose a financial burden on limited-resource farmers and reduce profitability. In addition to the cost of synthetic chemical insecticides, it adversely affects the environment due to toxic buildup in the soil over time and is a major cause of our food contamination. Socially disadvantaged small farmers are more vulnerable to losses due to lack of IPM knowledge, limited resources, and challenges in managing plant pests, as most IPM projects focus on large farms (Collins, 2022). The polyphagous nature of wireworms and their long cryptic life cycles render chemical control applications unsuccessful and pest estimation difficult under field conditions. Sweetpotato weevil pheromones are already known and are used effectively for monitoring weevils in multiple states. However, the semiochemicals for click beetles (wireworms) on sweetpotato are unknown and need further research. Identification of semiochemicals or sex pheromones of click beetles can be effectively used for sampling and monitoring wireworms in the field. Commercially available biological insecticides and entomopathogenic nematodes (EPNs) for the management of wireworms and other insect larval stages on sweetpotato tubers need to be evaluated. Laboratory, greenhouse, and field studies should investigate the efficacy of EPN strains in controlling wireworms. Promising EPN strains should be used in further field experiments for wireworm and root-knot nematode management. Studies are required to investigate the soil microbial community and the antagonistic effects of reducing parasitic root-knot nematode incidence using EPNs.

Sweetpotatoes are prone to many viral and soilborne diseases that can be vectored through the movement of infected planting material. Producing disease-free planting materials for growers, especially smallholder farms, is a big challenge. Smallholder farmers often use heirloom seed materials that have been passed on through generations, and very little is known about the virus infection status of these planting materials. One solution to the problems caused by sweetpotato "seeds" pathogens is to ensure that growers plant certified clean propagation material. However, there is an estimated 72% shortfall of clean plant units needed to cover all sweetpotato acreage (NCPN Network News, May 2018). Thus, there is a considerable demand for establishing certified nursery farms to produce clean "seed" in the sweetpotato industry. Besides, the high reinfection rate of viruses in production requires the farmers to frequently purchase virus-indexed propagation material, which greatly increases their financial input for propagation and production. Using high-throughput sequencing, we can characterize the virus infection status on those historical materials and identify the prevalence of other soilborne pathogens in current "seeds" production fields. By using different biotechnological approaches such as gene transformation or genome editing techniques, disease-resistant cultivars can be developed and are a promising strategy to control SPVD viruses in sweetpotatoes.

9.4 | Improving weed and water management strategies in sweetpotato cultivation

Weed management practices in smallholder and organic farms are expensive and are the most critical obstacle to the adoption of organic production or sustainable cultural practices (i.e., no tillage or minimum tillage). Adoption of cultivars tolerant to weed interference can be essential in integrated weed management in conventional and organic production. Development of erect and semi-erect vined sweetpotato germplasm could allow increased tillage- inter row cultivation later into the season, as the vines would not completely cover space between the rows. Additional research is required to identify and develop sweetpotato genotypes that are fast growing and have semi-erect to erect canopy architecture that may provide other weed and insect management strategies for sweetpotatoes.

Climate change is leading to increased extremes in droughts and floods, in both frequency and intensity. Because of this uncertainty in water supply, it is becoming more necessary to understand the role water has in sweetpotato cultivation, including WU, WUE, and runoff water quality and quantity. Further research is required to measure and calculate WU and WUE in the cultivar trials being conducted in the Southeastern United States. Also, it is essential to measure runoff quality and quantity at the onset of sweetpotato field experiments. The findings from these studies can be used to inform a hydrologic crop model to help simulate future management possibilities. Different crop models have been reported and evaluated for predicting future WU change from climate variability. Some of these models have predicted reduced rainfall, thus modifying evaporation and runoff and indicating an increased need for irrigation water. Similar crop models need to be developed for understanding WU, WUE, and runoff in sweetpotato production for different cultivars and geographical areas. Improving our knowledge on WU, WUE, and runoff for sweetpotato production in North America will allow for more informed management decisions leading toward increased sustainability of production and water supplies. Model testing and improvement with field experiments would require a coordinated international effort and long-term commitment to sweetpotato research.

10 | CONCLUSIONS

In recent years, there is a growing demand and interest in sweetpotato cultivation, and the number of projects and scientists working on sweetpotato research has increased. Smallholder farmers have realized that growing sweetpotatoes is beneficial, and the increased demand may be due to the promotion of the storage root's health benefits. The sweetpotato crop also has fewer insect pest problems than other storage root crops, except for sweetpotato weevil and wireworms, which cause significant damage in some of the sweetpotato growing areas.

The current review demonstrates the need for research to develop new sweetpotato genotypes and agricultural practices that maximize consumer sensory experiences and health benefits. It may enhance the interest of small- and mid-size organic farmers in adopting purple or other specialty sweetpotato cultivars as a niche market crop. Advances in sweetpotato chemistry and processing research will help to add value and increase consumption. Novel sweetpotato genetic materials with resistance to potyviruses will be developed by gene editing and can be used by smallholder farmers. Germplasm evaluations will contribute to safeguarding and utilizing the genetic diversity of the USDA sweetpotato germplasm collection and its crop wild relatives in genetic studies and breeding programs. EPNs that effectively control wireworms and other insect larval stages will be identified and used in smallholder and organic farms. A method of using honeybees as an environmental biomonitor to detect pathogens in sweetpotato cultivars will be developed. Identifying the antagonistic effects of EPNs and underground semiochemicals involved will help to develop integrated management tools for smallholder farms. Increased knowledge on WUE and runoff for sweetpotato production in North America will allow for more informed management decisions leading toward increased sustainability of production and water supplies. Improving the irrigation water quality and availability may increase yield and reduce pest incidence. Using endophytic and mycorrhizal fungus holds promise in increasing storage root yield and will be helpful for organic and smallholder farms. The information provided in this compiled review also will help to enhance economic efficiency and increase farm income, sustainability, and viability of socially disadvantaged small farms.

AUTHOR CONTRIBUTIONS

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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