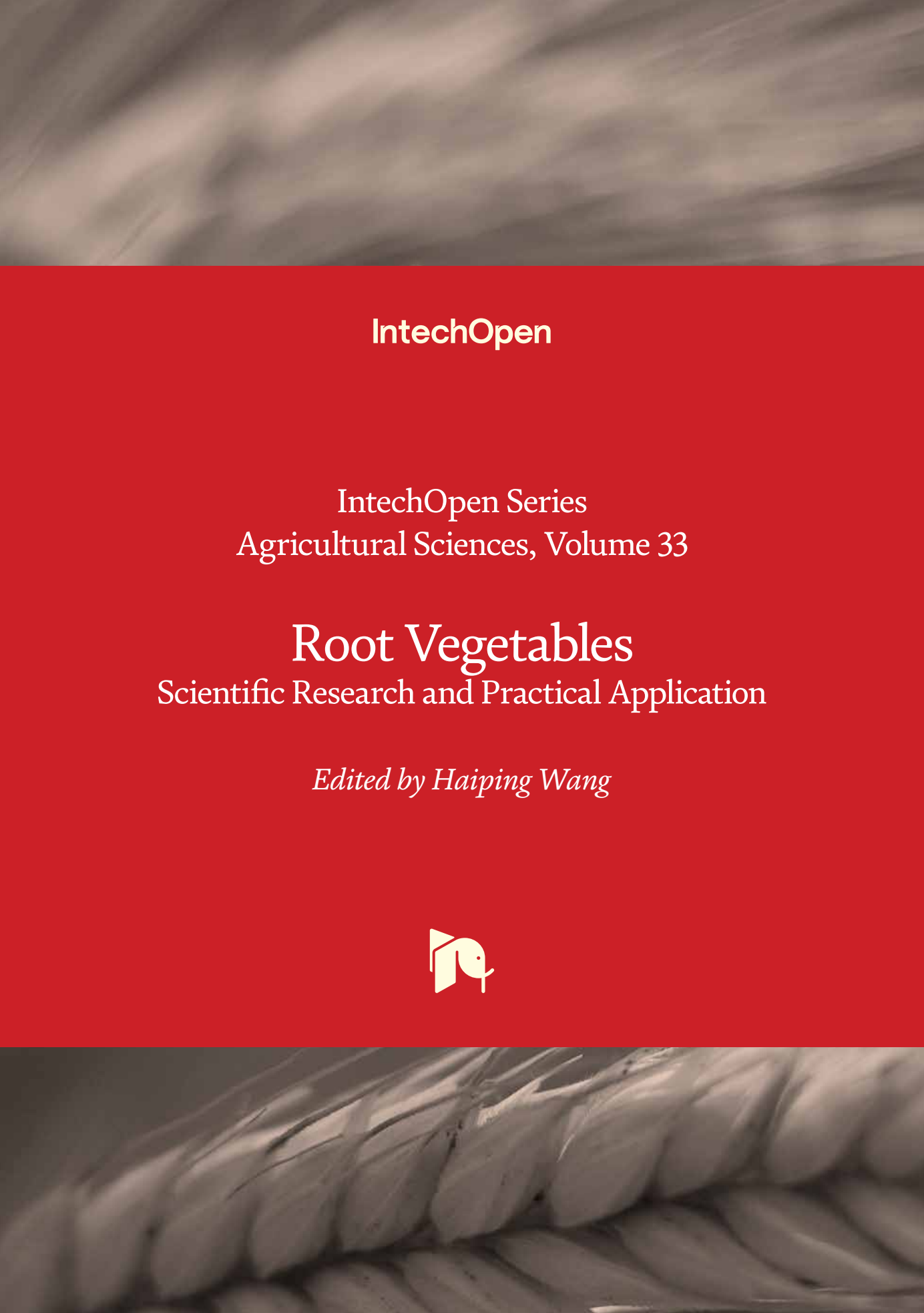




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Root Vegetables

Scientific Research and Practical Application

Edited by Haiping Wang



Root Vegetables - Scientific Research and Practical Application

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Contributors

Alfredo Morales, Alysson Roberto Baizi e Silva, Bian Xiaofeng, Catherine Yemisi Babatuyi, Dania Rodríguez, Ifra Aslam, Iván Javier Pastrana Vargas, Jia ZhaoDong, Muhammad Aijaz Ahmad, Peiyong Ma

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Aims and Scope of the Series

The importance of agriculture cannot be overstated. It helps sustain life, as it gives us the food we need to survive and provides opportunities for economic well-being. Agriculture helps people prosper around the world and combines the creativity, imagination, and skill involved in planting crops and raising animals with modern production methods and new technologies. This series includes two main topics: Agronomy and Horticulture, and Animal Farming. This series will help readers better understand the intricacies of production agriculture and provide the new knowledge that is required to be successful. The success of a farmer in modern agriculture requires knowledge of events happening locally as well as globally that impact input decisions and ultimately determine net profit.

Meet the Series Editor



W. James Grichar has been employed with Texas A&M AgriLife Research for over 45 years with an emphasis on research in agronomy, plant pathology, and weed science. He obtained his BS from Texas A&M in 1972 and his Masters of Plant Protection in 1975. He has published 195 journal articles, over 330 research reports and briefs, 11 book chapters, and over 300 abstracts of profession meetings. He also directs research in many crops including corn, grain sorghum, peanuts, and sesame. He has held various positions in different professional societies including the American Peanut Research and Education Society, Southern Weed Science Society, and Texas Plant Protection Conference in addition to being Associate Editor for Peanut Science and Weed Technology. Significant accomplishments have included spearheading efforts to determine the optimum planting time for soybean production along the upper Texas Gulf Coast. These efforts have shown growers that soybean yields can be improved by 10 to 20% by following a late March to early April plant date. He also has been instrumental in developing a herbicide program for peanut production in the south Texas growing region. Through the development and use of herbicides that are effective against major weed problems in the south Texas region, peanut yields have increased by 25 to 30%.

Meet the Volume Editor



Haiping Wang is a full-time Research Scientist and Professor in the Department of Germplasm Resources, Institute of Vegetables and Flowers, Chinese Academy of Agricultural Sciences (IVFCAAS). He is also the chief of the Department of Germplasm Resources' innovation team. He researches vegetable genetics to collect germplasm and preserve the diversity of the National Mid-term Genebank for Vegetable Germplasm Resources in China. His areas of interest include genetic diversity and phylogenetic development of vegetable germplasm resources, construction of core vegetable germplasm, and innovative utilization of vegetable germplasm based on modern biotechnology. He also collaborates with the garlic and ginger production industries and with consumers. Prof. Wang is the author/co-author of more than 100 publications in scientific journals and 11 book chapters. He is also a reviewer for several journals.

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Preface

Root vegetables are essential, and among them, tuber vegetables have the dual characteristics of both food and vegetables, playing an important role in people's diet. Tuber vegetables, as a widely cultivated crop category worldwide, play an irreplaceable role in ensuring food security, improving nutritional quality, promoting economic development, and adapting to the ecological environment. They are a key force supporting people's livelihoods and industrial development. Cassava, sweet potato, and yam, as the core varieties of tuber vegetables, each have their own advantages for livelihood security and industrial development. Their importance, production characteristics, and differences in variety are significant. This book introduces the important role of root vegetables and explains how to produce them better, focusing on variety selection, field management, and pest control during planting. At the same time, taking cassava, sweet potato, and yam as examples, it focuses on introducing these three crops from different perspectives, such as nutritional composition, breeding, production, and germplasm resource protection through individual discussions. In summary, this book will provide readers with a comprehensive understanding of root vegetables from multiple perspectives.

I would like to thank all the authors who contributed to this book. My sincere thanks also to the staff at IntechOpen for their assistance throughout the publication process.

Haiping Wang

Institute of Vegetables and Flowers,
Chinese Academy of Agricultural Sciences,
Beijing, China

Chapter 1

Vegetables and Beneficial Roles in Diets of Different Age Groups: A Review on Microbial Effects

Catherine Yemisi Babatuyi

Abstract

Vegetables are perishable plants that have a short lifespan, and due to that, they are prone to microbial contamination easily, which causes nutrient depletion. Depletion of nutrients and microbial contamination do affect different age groups health. The age groups consist: under 5 years of age, the young child, adolescents, adults and aged. Fruits and vegetables are very rich in micronutrients that the body needs for regular body enhancement to propagate health living in minute amount. Their effects are easily noticed in the body when found in limited amounts. Different fruits and vegetables contain different micronutrients. It is available to consume different varieties so that the body can utilize effectively available nutrients. Micronutrients are small nutrients the body requires to enhance good health. They are the minerals and vitamins mostly found in fruits and vegetables. Examples are the vitamins B, B12, C, D, E, K, etc., while the minerals are iron, calcium, zinc, potassium, magnesium, etc. The body needs these nutrients from vegetables at different stages of life. Microbial contamination does affect the supply of these nutrients in the body from the fruits and vegetables, hence resulting in infection. This chapter was divided into five groups, in which the difference between the leafy and root vegetables was discussed, including their soil vegetation storage period, and required quantity per age group. Other discussed issues were vegetables and their classes, nutritional compositions and health benefits, some root vegetables and health interventions, applications in food processing, and microbial influences.

Keywords: vegetables, beneficial roles, age groups, microbial influence, future review

1. Introduction

Root vegetables are underground plants rooted in the ground or on the soil surface, which include some that are tuberous, in rhizomes, in bulbs, some are just leafy vegetables, and some are in corms [1]. They are portions of edible herbaceous plants. They are all categorized as culinary, because they offer potential dietary energy calorie intake in the form of polysaccharides, which are broken down to simple sugars during digestion. Some examples are dark leafy vegetables (spinach, kale, arugula,

lettuce, etc.), potatoes, carrots, onions, etc. They are rich in both macronutrients and micronutrients for body metabolic functions [2]. They are requisite components found in food recipes. These vegetables are consumed across all different continents, but differ in some factors that determine their availability such as the areas, species, soil structures and weather topography. This influenced the temperature, humidity, water activity, oxygen, etc. [3].

The beneficial roles of vegetables are numerous in health system, especially in nutrition and diet therapy, where they function [1]. The leafy vegetables are rich in some vitamins such as vitamin B, B12, C, D, and K, and minerals such as calcium, zinc, potassium and phosphorus. Examples of root vegetables are sweet potatoes, turnips, carrots, beets, and are rich in dietary fiber, minerals, vitamins, antioxidants, prebiotics, etc., and function in food therapy in the management of oxidative stress disorders [4].

The leafy and root vegetables do make great cuisines that are lovely consumed by different age groups such as under 5 child (6 months to 5 years), young child (5 to 12 years), adolescents (13 to 19 years), adults (20 to 59 years) and aged (60 above). Their consumption rate differ with the quantity to consume at a time and the type has been researched upon with data, as many diseases have resulted from low consumption of vegetables at the right time, the body's metabolism demands their functions [5].

The shelf life of the vegetables is short; they need to be consumed within a short time before losing the vital nutrients to decomposition as a result of deterioration, which can be caused by microbial activity or by innate enzymes [6]. There are some diseases associated with a lack of or insufficient consumption rate, as well as functional roles they do play in averting, managing or healing of both leafy and root vegetables through food therapy. Therefore, the nutritional roles in the diet of different age groups are crucial to good living, which is essential to the lifestyle and determine the healthy status of the individual and as well as the nature.

This book chapter focuses on the nutritional composition of vegetables, effects on the different age groups, functional benefits and applications and microbial implications.

2. Vegetables and their classes

Vegetables are herbaceous plants that consist of edible leafy vegetables, seeds, roots and stems, which come from different families. The root vegetables are cultivated in soil free of cluster organic wastes, loose soil structure with free water passage and adequate sunlight. They grow between pH levels of slightly acidic and slightly alkaline (6.5 and 7.5) as reported by [7]. Likewise, the leafy vegetables have similar ecologically friendly growing conditions of friable soil free of clumps of organic matter that allows easy flow of water passage with a pH between slightly acidic to near neutral (5.6 and 6.8). **Figure 1a** and **b** represents the pictorial view of both leafy and root vegetables below.

2.1 Nutritional composition and health benefits of vegetables

Vegetables are very rich in some macronutrients and micronutrients that perform health-functional roles. Some nutrients are available for body enrichment when they are processed. **Table 1** reveals the analyzed data of some root vegetables [1].

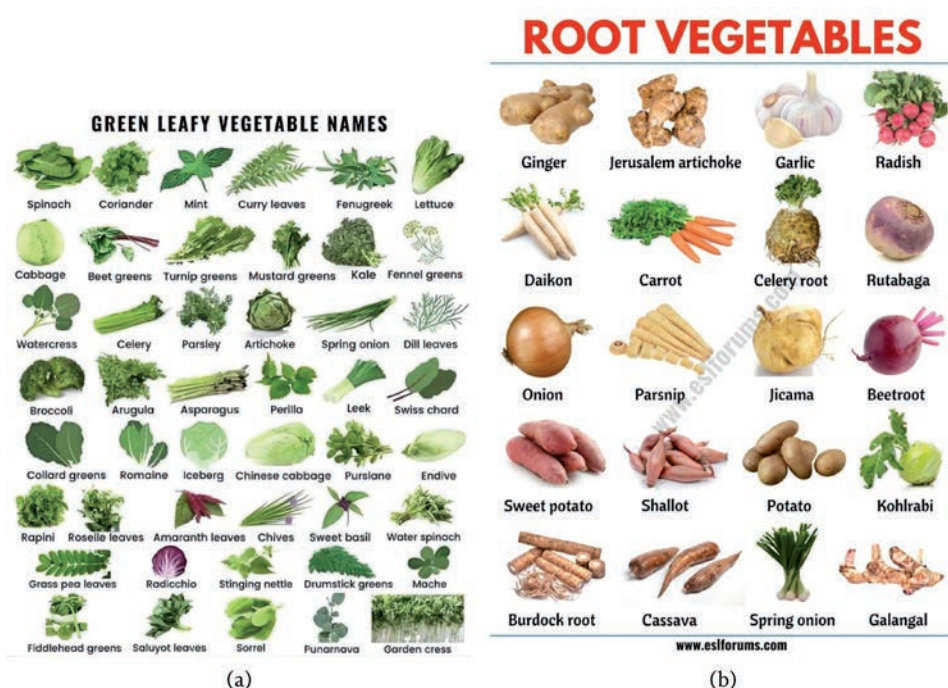


Figure 1.
(a and b) Pictorial view of leafy and root vegetables. Source: [eslforums.org](http://www.eslforums.org).

Components	Carrot	Beetroot	Celery root	Parsley root	Radish	Turnip	Horseradish
Moisture content (g/100 g)	88.3	87.6	88.0	85.3	95.3	91.9	75.0
Energy (kcal/100 g)	41.0	43.0	42.0	49.0	16.0	28.0	81.0
Proteins (g/100 g)	0.93	1.61	1.5	2.6	0.68	0.9	4.5
Lipids (g/100 g)	0.24	0.17	0.3	0.5	0.1	0.1	0.6
Carbohydrates (g/100 g)	9.58	9.56	9.2	10.5	3.4	6.43	18.1
Dietary fiber, total (g/100 g)	2.8	2.8	1.8	4.2	1.6	1.8	7.3
Calcium (mg/100)	33.0	16.0	43.0	43.0	25.0	30.0	78.0
Iron (mg/100 g)	0.3	0.8	0.7	1.1	0.34	0.3	1.2
Magnesium (mg/100 g)	12.0	23.0	20.0	27.0	10.0	11.0	43.0
Phosphorus (mg/100 g)	35.0	40.0	115.0	77.0	20.0	27.0	120.0
Potassium (mg/100 g)	320.0	325.0	300.0	339.0	233.0	191.0	740.0
Sodium (mg/100 g)	87.0	78.0	100.0	49.0	39.0	67.0	7.0
Zinc (mg/100 g)	0.24	0.35	0.33	0.6	0.28	0.27	1.40
Copper (mg/100 g)	0.06	0.075	0.07	0.14	0.05	0.085	0.23
Selenium (µg/100 g)	0.1	0.7	0.7	ND	0.6	0.7	ND
Vitamin C (mg/100 g)	5.9	4.9	8	45.0	14.8	21.0	114.0

Components	Carrot	Beetroot	Celery root	Parsley root	Radish	Turnip	Horseradish
Thiamin (mg/100 g)	0.066	0.031	0.05	0.1	0.012	0.04	0.14
Riboflavin (mg/100 g)	0.058	0.4	0.06	0.086	0.039	0.03	0.11
Niacin (mg/100 g)	0.983	0.334	0.7	2.0	0.254	0.4	0.6
Pyridoxine (mg/100 g)	0.138	0.067	0.165	0.23	0.071	0.09	0.18
Folate, total (µg/100 g)	19.0	109.0	8.0	180.0	25.0	15.0	37.0

Source: [1].
ND = Not determined.

Table 1.
Nutritional composition of root vegetables.

This reflected the nutritional importance of the quality of some root vegetables in the diet, which can help in the body's metabolic function. Moreover, the leafy vegetables are known to be rich in micronutrients, dietary fiber, essential amino and essential fatty acids.

etc. They do have some health functions, just like some root vegetables, as shown in **Table 2**. They can be used or serve as nutritionally enriched food products in combating deficiencies, containing bioactive compounds such as omega-3-fatty acids, carotenoids, etc., as reported [8] during their research, and could be a good source of healthy carbohydrates, with less calories and fat. There are some nutritional roles stated below that they perform. Some are carotenoids, vitamin A, C, K, E, B, B9, folic acids, iron, etc.

Both vegetables can function as functional/nutraceutical in bridging the gap in the health sector or/and management of oxidative stress-related diseases and/or ailments through the action of anti-inflammatory and antioxidant properties intervention in some conditions such as high blood pressure, anemia, diabetes, stroke, and the rest. They may also function in the improvement of immune system, skin, heart, bone and gut microbiomes, which have been reviewed in many research works. **Table 3** states some nutritional composition of some research work.

Vegetables	Calories	Proteins	Sugars	Carbohydrate	Fat	Fiber
Kale	43	3.5 g	1.4 g	6.3 g	1.4 g	4.7 g
Collard greens	62	5.2 g	0.8 g	10.7 g	1.4 g	7.6 g
Spinach	7	0.9 g	0.1 g	1.1 g	0.1 g	0.7 g
Cabbage	22	1.1 g	2.9 g	5.2 g	0.1 g	2.2 g
Watercress	4	0.8 g	0.1 g	0.4 g	0 g	0.2 g
Romaine lettuce	8	0.6 g	0.6 g	1.6 g	0.1 g	1 g
Arugula	3	0.3 g	0.2 g	0.4 g	0.1 g	0.2 g
Bok choy	9	1.1 g	0.8 g	1.5 g	0.1 g	0.7 g
Beet greens	8.4	0.8 g	0.2 g	1.6 g	0.1 g	1.4
Swiss chard	6.8	0.6 g	0.4 g	1.4 g	0.1 g	0.6 g

Source: [8].

Table 2.
Nutritional composition of leafy vegetables.

Food products	Type of study	Form of vegetable/ compound tested	Effect	Source
Carrot	<i>In vitro</i>	Carrot powder	Antioxidant activity: a potential inhibit α -galactosidase during fermentation shown by polyphenols Regulation of gut microbiota diversity	[9]
Beetroot	<i>In vivo</i> /people	Beetroot juice	Systolic blood pressure was lower among people consumed beetroot juice supplementation. Potential nitrate-independent effect of beetroot juice	[10]
Carrot	<i>In vivo</i> /rats	Fermented carrot juice	Regulation of glucose level Regulation of insulin sensitivity Increase of short-chain fatty acids in the small intestine Increase of microbiota abundance	[11]
Carrot	<i>In vivo</i> /rats	Carrot seed extract	Increase level of thyroxine Decrease of spatial memory and passive avoidance memory	[12]
Carrot	<i>In vivo</i> /women	Carrot seed	Female sexual function index (FSFI) questionnaire improved (mainly higher desire, higher satisfaction, and lower pain involving sexual intercourse)	[13, 14]
Beetroot	<i>In vivo</i> /people	Beetroot juice	Ingestion of beetroot juice increased blood flow to the brain and enhanced exercise performance	[15]
Carrot	<i>In vivo</i> /people/ meta-analysis	Carrot and its products	Dietary carrot intake is associated with decreased risk of breast and prostate cancer	[16, 17]
Parsley	<i>In vivo</i> /mice	Polyphenolic fraction of parsley	Decreased depressive behavior (decreased immobility time) Decreased anxiolytic behavior (tendency for discovery in the center and illuminated areas)	[18]
Parsley	<i>In vivo</i> /rats	Parsley leaf extract	Improvement of fetuses metabolic morphology of pregnant diabetic rats due to reduce diabetic mothers	[19]
Parsley	<i>In vivo</i> /rats	Parsley seed Extract	Total cholesterol, triglycerides, and LDL cholesterol decreased Cholesterol HDL increased	[20]
Radish	<i>In vivo</i> /people	Radish, root	Increased calcium oxalate excretion in both women and men	[21]
Horseradish	<i>In vitro</i> /human peripheral blood mononuclear cells (PBMC)	Horseradish Extract	Extract concentration-dependent inhibition of anti-inflammatory response to lipopolysaccharide (LPS) in terms of TNF- α release	[22]
Celery	<i>In vivo</i> /mice	Fermented celery Juice	Increased relative abundance of beneficial bacteria in gut microbiota Increased ratio of firmicutes/ bacteroidetes Decreased relative abundance of harmful bacteria (<i>Alloprevotella</i> and <i>Helicobacter</i>)	[23]

Food products	Type of study	Form of vegetable/ compound tested	Effect	Source
Celery	<i>In vivo</i> /mice	Celery extract	Reduction of lipid peroxidation of brain Increase in glutathione peroxidase activity	[24]
Celery	<i>In vivo</i> /women	Celery seed	Improved higher desire, higher arousal, and lower pain involving sexual intercourse on the female sexual function index (FSFI) questionnaire	[25]
Celery	<i>In vivo</i> /people	Celery seed extract	Systolic blood pressure decreased by 11 mmHg on average. Diastolic pressure decreased by 8 mmHg on average	[26]

Table 3.
Comparative studies of some root vegetables and their health interventions.

2.2 Application of vegetables

The application of vegetables in food processing is numerous, and they are usually served in various cuisines to human ranging from young to old. Some are listed below:

Soups and stews: Pureed or diced root vegetables like carrots, sweet potatoes, and turnips add depth, texture, and natural sweetness to soups and stews, enhancing both nutrition and flavor.

Snacks and chips: Dehydrated root vegetable slices or powders offer a nutrient-dense alternative to conventional snack products, appealing to consumers seeking better options [27].

Baked products: Root vegetable purees and powders, such as sweet potato or carrot, can add moisture, natural sweetness, and nutritional value to breads, muffins, and other baked products while reducing the need for added sugars or fats [28].

Ready-to-eat products: Root vegetables are ideal for ready-made meals, contributing both flavor and a nutrient boost to pastas, grain bowls, and frozen entrees.

Beverages and smoothies: In powdered or pureed form, root vegetables like beets and sweet potatoes provide color, antioxidants, and functional benefits in smoothie bases and powdered drink formulations.

2.3 Vegetables and their lifespan conditions

The storage conditions differ as their moisture content varies, and this also determines their lifespan. They are easily prone to microbial decomposition as a result of their nature, which leads to spoilage and nutrient leaching or decomposition [29]. These storage conditions expand their shelf life as state in **Table 4** from studies carried out. When the leafy greens are washed or dressed, they can be consumed within 3 days, while the unwashed vegetables can stay in the refrigerator for several days with stable electricity and still be fresh such as lettuce, etc. Examples of leafy vegetables are spinach, kale, jute leaf, etc. The root vegetables usually survive for some weeks depending on the type and storage conditions such as dry and cool environment with humidity, which extends their shelf life. Humidity plays a crucial role in the prevention of root vegetables maintaining their freshness from shriveling or/and

Food item	Conditions	Container	Shelf life	Avoid
Apples	Refrigerator	Plastic bag	2 weeks plus	Cabbage, leafy greens, carrots
Pears	Room temperature, then refrigerator	Loose the plastic bag in fridge	Up to 2 weeks	Cabbage, leafy greens, carrots
Grapefruit, oranges	Refrigerator	Loose or open container	Room temp: 1–2 weeks Fridge: 2 weeks plus	N/A
Lemons, lime	Room temperature, then refrigerator	Loose or open container	Room temp: 1–2 weeks Fridge: 2 weeks plus	Plastic bags, apples, pears, and bananas
Mangoes	Room temperature, then refrigerator	Loose or open container	A few days to 2 weeks	Apples, pears
Winter squash	Cool and dry	Loose or open container	3 to 6 months	Banana
Ginger	Refrigerator	Sealed container	3 weeks plus	N/A
Parsnips, beets, radishes, rutabaga, turnips	Loose or open container	Sealed container, remove green tops	3 weeks plus	N/A
Carrots	Refrigerator	Sealed container, remove green tops	2 to 3 weeks	Apples, pears
Onions, garlic	Cool and dry	Loose or open container	2 weeks plus	Refrigerator, plastic bags
Potatoes, sweet potatoes	Cool and humid, and dark	Loose or open container	Potatoes: 3 weeks Sweet potatoes: 1 to 2 weeks	Refrigerator, plastic bags
Head lettuces	Refrigerator	Sealed container, unwashed	Up to 1 week	Apples, pears, moisture
Escarole, kale, watercress, curly endive	Refrigerator	Sealed container, unwashed	Up to 2 weeks	Apples, pears
Cabbage	Refrigerator	Loose then sealed when cut	Up to 3 weeks	Apples, pears
Broccoli, cauliflower	Refrigerator	Sealed container	Up to 2 weeks	Apples, pears

Source: [29].

Table 4.
Lifespan conditions of some food items.

losing their moisture content and water activity (inert water). Examples can be carrots, sweet potatoes, beets, turnips, etc. The season of most vegetables spans through 4 to 6 months, while leafy vegetables are within 28 to 180 days [30].

However, pre-storage treatments are sometimes given to some root vegetables such as hot-water (blanching) treatment techniques, which prolong their lifespan and prevent microbial infestation diseases due to spoilage. Likewise, exposure to some irradiations such as ultraviolet (UV) lamps or ozone (O₃) prevents microbial metabolic activities resulting in spoilage and diminishing of nutrients, hence elongate their

shelf-life spoilage [31]. Storing the vegetables correctly extends their shelf life. In spite of different methods employed in prolonging the shelf life of different vegetables by inhibiting the metabolic activities that lead to deterioration, they are persistently liable to enzymatic activities during storage [31].

2.4 Root vegetables and their consumption levels among different age groups

Root vegetables do have a significant importance in the diet of people and cut across all different age groups. They are needed in different quantities among age groups and are specific in action in their requirements. The formative age group requires vegetables for psychosocial and cognitive development, which is essential for their dietary lifestyles and development in life [32]. This point was also buttressed in research that at the formative age, the behavioral characteristics such as knowledge, attitude, etc., would have been developed to determine their adulthood [33]. These factors include influence from parents, education, cultural norms, finances, etc. There are collated reports of nutrient deficiencies and imbalances across different age groups about the negative implications of deficiencies that have led to negative health outcomes among these age groups. These include stunted growth and development in children, while cognitive function and physical development may be impaired in adolescents, and a reduction of quality of life with chronic diseases can be noticeable in adults [33, 34].

The age groupings are highlighted below with the implications.

- i. Infant and early child: This range from 6 months to 5 years can be served 1 to 2 vegetables per day. Symptoms of protein-energy malnutrition (PEM) with increased susceptibility to infections are frequently common and wasting (low weight for height) due to an immune system problem.
- ii. Early child to young child: This range from 6 to 12 years can be served 4 to 5 of vegetables per day. It can be increased to 6 as the need warrants. It can lead to stunted growth and cognitive function when not adequate. They do have problems with the immune system, developed rickets (bone softening), anemia and goiter and other thyroid problems, affecting brain development and growth iodine deficiency.
- iii. Adolescent to adult: This ranges from 20 to 59 years and can serve 2 to 3 vegetables per day. It can be increased if the needs warrant. Iron deficiency is experienced in girls due to menstruation, hindering development of strong bone during peak growth years (calcium and deficiencies) and immune function impairment.
- iv. Young adult do experience fatigue, and weakened immune systems due to micronutrient deficiencies. Cognitive impairment and depression occur due to malnutrition and pose the risk of diseases of the heart, cancer and diabetes due to nutritional imbalances.
- v. Older adult: Older adults start from 60 years above and can be served 2 to 3 vegetables per day. It can lead to decreased appetite, fatigue, reduced cognitive function and reduced quality of life when not adequate.

It has been noted that the intake of vegetables among young children and adolescents has been recorded as low, which is usually needed during their developmental age and calorie intake and because vegetables were not consumed at the right time and quantity for their developmental growth, it resulted in micronutrient deficiencies. Some factors usually affect the consumption habit of vegetables in diet right from childhood age, which include age, lack of knowledge on healthy food intake, level of caregiver's education, finances, socioeconomic status, etc. [35]. It has been reported from research works that in low-income countries, the rate of consumption of vegetables among school-age children declined compared to advanced countries [36]. Likewise, diseases such as obesity resulted due to over consumption of high-calorie foods and nutrient-poor (lack of micronutrients) among young child-adolescents, known as childhood obesity, which occurred as a result of overweight [37, 38].

2.5 Microbial influence on the vegetables

The influence of microorganisms on vegetables either leafy or root have been a great impact on the preservation of vegetables. This has posed a great challenge globally in sustaining them for a longer period after harvest, even with the technology of post-harvesting. Prevention of infestation of microorganisms has become inevitable so far, as ripening and senescence occur during metabolic activity, which can result in developmental deterioration and spoilage [39]. These factors, according to research, include plant surface exudates, topography, developmental stage, surface morphology and post-harvest handling techniques [21]. The loss of vegetables due to deterioration as a result of spoilage is also a threat to public health, as it usually involves foodborne diseases. The implications of the deterioration of vegetables are numerous, including economic loss, foodborne illness and infection, shortage of supply, wastage, etc. This is a clarion call to all governments at every parastatal to awaken to this global call before it becomes a pandemic issue.

The handling and the condition of storage influence the quick deterioration of the vegetables. There are different types of causes of spoilage, which have been categorized into microbial, chemical, physical and environmental conditions [40]. They are:

- i. Microbial damage occurs where there is degradation of the connective tissues of the plant due to microbial infestation such as bacteria and fungi, especially *Pseudomonas* and *Erwinia* commonly cause infection.
- ii. Chemical damage occurs when there is oxidation due to the enzymatic reactions of innate enzymes during moisture loss, causing degradation and quality loss. Ethylene exposure can also affect the lifespan.
- iii. Physical damage occurs during harvesting, handling and storage, causing bruises and injury to the vegetable, prompting them to spoil, which can lead to microbial infestation
- iv. Environmental damage occurs where there is fluctuation in storage temperature caused by a shift in the humidity.

Some examples of deterioration due to different spoilage are highlighted in **Table 5** below.

Causative agent	Infection caused	Produce affected	Signs
<i>Erwinia carotovora</i> subsp. <i>Carotovora</i>	Bacterial soft rot	Many vegetables including leafy crucifers, lettuce, endives, parsley, celery, carrots, onions, garlic, tomatoes, beets, peppers, cucumbers and fruits.	Slimy, mushy and browning texture off-flavor.
<i>Pectobacterium carotovorum</i> , <i>Ceratocystis fimbriata</i>	Bacterial soft rot, blackleg (stem rot), tuber soft rot, black rot	Beet, potato, sweet potato	Slimy, becoming mushy and unpleasant odors
<i>Leuconostoc mesenteroides</i>	Fermentation	A wide variety of fruits and vegetables	Appearance of moldy or slimy.
<i>Geotrichum candidum</i>	Sour rot	Asparagus, onions, garlic, carrots, parsley, parsnips, lettuce, endives, tomatoes	Discoloration and damage to the root.
<i>Pythium</i> spp.	Rot, damping off, wilt, soft rot	Parsley, parsnip	Wilting, moldy or slimy appearance.
<i>Cladosporium</i> , <i>Trichoderma</i> , <i>Sclerotinia sclerotiorum</i>	Green mold rot, watery sift rot	Vegetables	Wilting, dry and brittle leaves, off-odors
Pest damage	Insects, rodents, and other pests	Root vegetables	Pest infestation (bruises, cut, bite etc.)
<i>Agrobacterium</i> spp.	Tumor	Carrots	Slimy, rotten and discoloration surface

Source: [21, 39, 40].

Table 5.
Vegetables and their spoilage agents.

3. Conclusion and future review

Vegetables are plants that are part of food calorie intake needed to enhance the body metabolic activities. Consumption rate at different age groups is very crucial to nutrition management. Prevention of different contaminations should be a global intervention for remarkable sustainability. The comparative study of vegetables is of great value, and it should be reviewed yearly to ascertain the healthy status of an individual or an entity. The consumption rate of different age groups is very essential and it has to be monitored to provide a healthy living, which invariably give a hopeful future of the youth. Likewise, the microbial infestation, one of the types of contamination and chemical are of concern in sustaining the healthy future. An enlightening societal program should be reviewed from time to time in having friendly environment free of hazardous pollution from wastes and chemical metabolites and their effects on humans through the consumption of contaminated vegetables.

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Author details

Catherine Yemisi Babatuyi
Department of Nutrition and Dietetics, Federal University of Technology,
Akure, Nigeria

*Address all correspondence to: cybabatuyi@futa.edu.ng

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Root Vegetable Health: Diagnosis, Prevention, and Control

Muhammad Aijaz Ahmad and Ifra Aslam

Abstract

Root vegetables are pivotal crops globally, furnishing essential nutrients and energy for human sustenance. Nevertheless, these crops are vulnerable to an array of biotic and abiotic stresses, compromising their health, productivity, and nutritional quality. This chapter provides an exhaustive review of the predominant health issues affecting root vegetables, encompassing fungal, bacterial, viral, and nematode diseases, as well as insect pests and abiotic stresses. We delineate the diagnostic protocols for root vegetable health issues, incorporating visual symptomatology, laboratory assays, and cutting-edge molecular diagnostic techniques. Moreover, we elucidate prevention and control strategies, including cultural practices, resistance breeding, biological control, and integrated pest management (IPM) approaches. Furthermore, we examine the impact of climate change, soil degradation, and water scarcity on root vegetable health, underscoring the imperative for sustainable and resilient production systems. By synthesizing current scientific knowledge and research findings, this chapter aims to provide a valuable resource for researchers, extension agents, and growers seeking to maintain healthy, productive, and sustainable root-vegetable crops.

Keywords: biological control, integrated pest management, soil-borne diseases, sustainable agriculture, plant disease diagnosis, disease prevention, crop health, root vegetables

1. Introduction

Roots are non-photosynthetic plant organs that arise from the radicle and grow geotropically, exhibiting specialized structures like root hairs, which facilitate water and mineral uptake from the soil [1], and providing structural support and anchorage [2], constituting approximately 20–30% of the total plant's volume [3]. Plant roots are classified into the two main types of flowering plants: taproot and adventitious root, due to differentiation in their root anatomy [4]. The taproot is the main central root that grows vertically downward and gives rise to the smaller lateral root system, mainly found in dicotyledonous plants, for example, leguminous plants, trees, and root vegetables [5, 6].

Vegetables are edible parts of herbaceous plants, including roots, stems, leaves, flowers, and sometimes immature fruits, essential for a well-balanced diet. Root vegetables are those where the main primary edible part is their roots, which store

nutrients underground and serve as essential crops worldwide [7–9]. Classed based on botanical origin, climate adaptation, and edible portions, such as carrots (*Daucus carota* L.), with water content (69.06 – 75.3%) [10, 11], macronutrients 23.63%, with lower fats; potato (*Solanum tuberosum* L.) and celery (*Apium graveolens* L.), with carbohydrates (9.2 g/100 g) and the important mineral electrolyte potassium (K) (300 mg/100 g) [12], a highly antioxidant root vegetable that has been less studied because researchers mostly focus on the stems and leaves, while the roots are less explored [13]; parsley (*Petroselinum crispum* Mill.), rich in folates (180 µg/100 g) [14], whose roots are used for taste in various food items [15]; beetroot (*Beta vulgaris* L.), organic beetroot with higher minerals content, K (356 mg/100 g), P, Mg, and Ca, and macronutrients (20.95%) [16]; radish (*Raphanus sativus* L.), characterized by higher water content (95.3%) and lower carbohydrates (3.4 g/100 g) [17]; turnip (*Brassica rapa* L.), with the lowest calorie value (28 kcal/100 g) among root vegetables [18]; horseradish (*Armoracia rusticana* G. Gaertn.), with a calorie value (81 kcal/100 g) and high concentrations of vitamin C (114 mg/100 g) and K (740 mg/100 g) [19]; sweet potato (*Ipomoea batatas* (L.) Lam.), with the highest starch content (20.4 mg/100 g) [20] among all root vegetables [18]. All root vegetables contain bioactive substances involved in various metabolic activities [21] and belong to the Apiaceae, Amaranthaceae, Convolvulaceae, and Brassicaceae families [22].

Due to their heavy cost of consumption [23], many root vegetables are threatening by the accumulation of various heavy metals [24–26], polycyclic aromatic hydrocarbons [27], and higher levels of nitrites and nitrates [28, 29]. Consuming these microplastic-based adolescent vegetables [26, 30] leads to dietary cancers [31, 32] and major health effects in children's [33]. While nitrate- and nitrate-rich food sources [28, 29] also have many beneficial impacts, such as nitrate-rich juice of the beetroot, which is a highly recommended dietary supplement [34] to cure the chronic obstructive pulmonary disease (COPD) [35].

Rhizosphere conditions refer to the dynamic environmental factors that directly surround plant roots and influence root development, nutrient uptake, and microbial interactions [36, 37]. The health and productivity of root vegetables are constantly threatened by both biotic and abiotic factors, which cause major crop losses annually due to various root infections, leading to significant yield reductions [38]. In this chapter, we investigate several root pathogens that adversely impact root vegetable crops. We provide the management strategies against the symptoms and losses of vegetable crops [39], that enable the timely intervention to mitigate diseases by emphasizing root vegetables productivity, and adopting the various control measures, and sustainable agriculture practices to address these diseases.

2. Understanding root vegetable pest: Biology, ecology, and behavior

Root vegetable pests, including insects, nematodes, and soil-dwelling organisms, are posing a significant threat to these crops [40]. Based on the taxonomic perspective, soil pests can be categorized into three main groups: (i) Insect pests: These include wireworms (*Agriotes* spp.), carrot rust flies (*Psila rosae*), cabbage maggot (*Delia radicum*), onion maggot (*Delia Antiqua*), sweet potato weevil (*Cylas Formicarius*), flea beetles (*Phyllotreta* spp.), and potato tuberworms (*Phthorimaea operculella*) [40, 41]. These are among the most destructive insect pests, as their larvae dig into roots and cause extensive damage [42]. (ii) Nematodes: This group includes root-knot nematodes (*Meloidogyne* spp.), cyst nematodes (*Globodera* spp.),

and stubby-root nematodes (*Trichodorus* spp. and *Paratrichodorus* spp.) [43, 44], which inhibit plant nutrient intake, resulting in impaired growth and low production [45]. (iii) Soil-dwelling mollusks and insects: These pests include slugs (*Arion* spp.) and snails (*Cornu aspersum*), which contribute to plant stress by creating holes and feeding scars on carrots, radishes, and potatoes, which directly leading to deformities and secondary infection. Mole crickets (*Scapteriscus* spp.) tunnel through the soil, damaging the roots, which disrupts the plant root anchorage [46].

These infections impair plant vigor, lower yields, and can result in crop loss [47]. A detailed understanding of the biology, ecology, and behavior of root pests is essential for developing specific integrated pest management strategies that effectively reduce crop losses, enhance resilience against infestations, and promote eco-friendly farming practices [48, 49].

2.1 Biological cycles of the root vegetable pests

Root vegetable pests are capable of a variety of biological modifications that enable them to survive in different soil conditions [50]. These adaptations include specific reproductive strategies involving the larval stage of the click beetles in wireworms, such as egg, larva, pupa, and adult stages. A five-year underground larval stage that undergoes the entire metamorphosis, leading to entering the roots by creating tunnels [40]. *Agriotes* spp. females reproduce sexually by laying eggs in the moist soil. Their (3–5 years) overlying generations larval stage makes their control very difficult [41, 42]. Root-knot nematodes cause significant infection in the root tissues by dividing in their second-stage juveniles (J2), and adult stages producing various feeding sites and gall formation [43, 44]. *Meloidogyne* spp. reproduce rapidly by parthenogenesis, that is, single female produces 1000 eggs per cycle [45]. In the life cycle of mole crickets three developmental stages: egg, nymph, and adult; among these, nymphs are the most actively involved in causing extensive root damage and spreading infections beneath the soil surface by crawling. *Scapteriscus* spp., especially their nymph stage, release 30–60 eggs, involved in destroying the root system by their extensive burrowing [46]. Physiological changes are also very helpful in understanding how the soil-dwelling pests interact with each other, which stimulates their survival in the soil. Root-knot nematodes involve the discharge of various enzymes by degrade the plant cell walls the forming a protective cyst that becomes dominant in various harsh conditions, surviving in the soil for long periods [44]. Mole crickets produce tunnels in the compacted soil debris with their specialized forelimbs that easily detect the vibrations in the soil. They enable themselves to resist dehydration through their specialized exoskeleton, which detects vibrations to help them navigate and cop with the predators [46]. These are the basic reproductive and physiological adaptations that help them thrive in subterranean environments [51].

By understanding these biological cycles, farmers can easily predict the peak vulnerability periods of attack, which enables them to develop more sustainable pest management strategies by targeting treatments and appropriate measures (**Figure 1**) [48, 52].

2.2 Ecological dynamics and environmental influences of the root vegetable pests

Root vegetable pests interact with their natural environment *via* challenging ecological processes, such as habitat preferences and environmental stresses. The rhizosphere plays a crucial role in plant health, nutrient uptake, and defense against pests

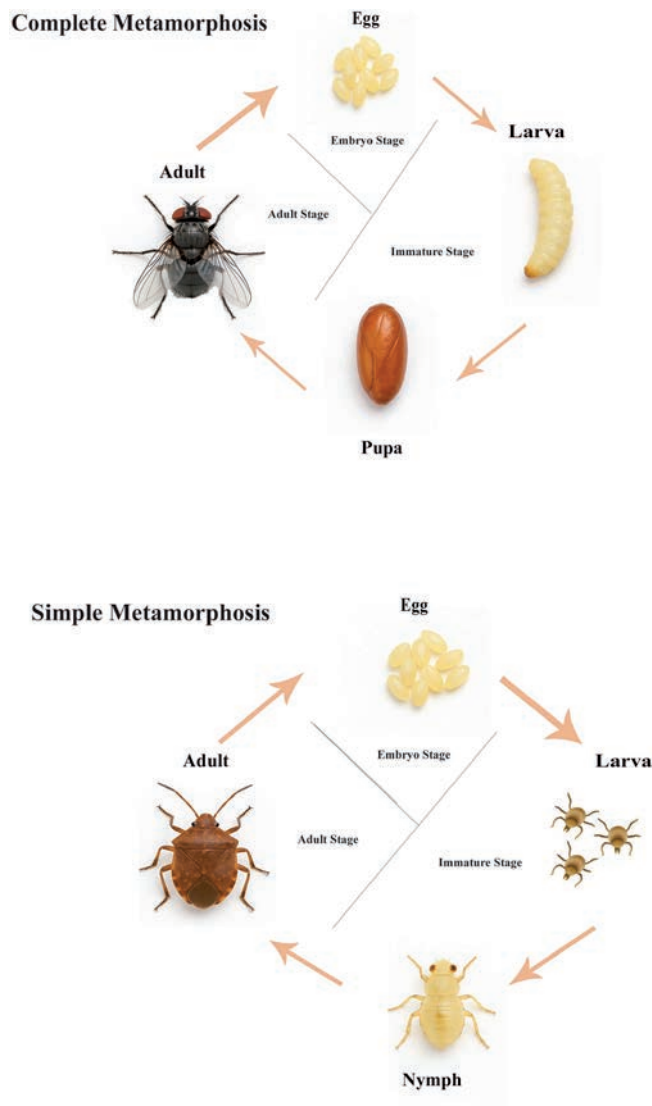


Figure 1.
Life cycle of wireworm (complete metamorphosis) and mole crickets (simple metamorphosis).

and diseases. Root vegetable pests interact with soil texture, soil structure, soil pH, nutrient availability, moisture levels, and organic matter. Climate warming reduces pest growth, shortening the insect life cycle by 10–15% with every 2% rise in temperature, and accelerates pest survival rates (30%) in winter [41, 53]. Their ecological roles extend beyond direct plant damage, influencing soil health and plant-microbe interactions [51]. By interacting with the soil microbiota and plant roots, the infection cycles of *Heterodera* spp. promotes its growth rapidly by interacting with particular rhizobacteria that promote the cyst formation [41, 53]. In *Diabrotica virgifera* larvae, the infection rate increases rapidly after interacting with *Fusarium* while feeding on maize roots [48, 52]. The root-vegetable pests ultimately change the chemistry of the rhizosphere and adversely affect beneficial root microbes. These environmental

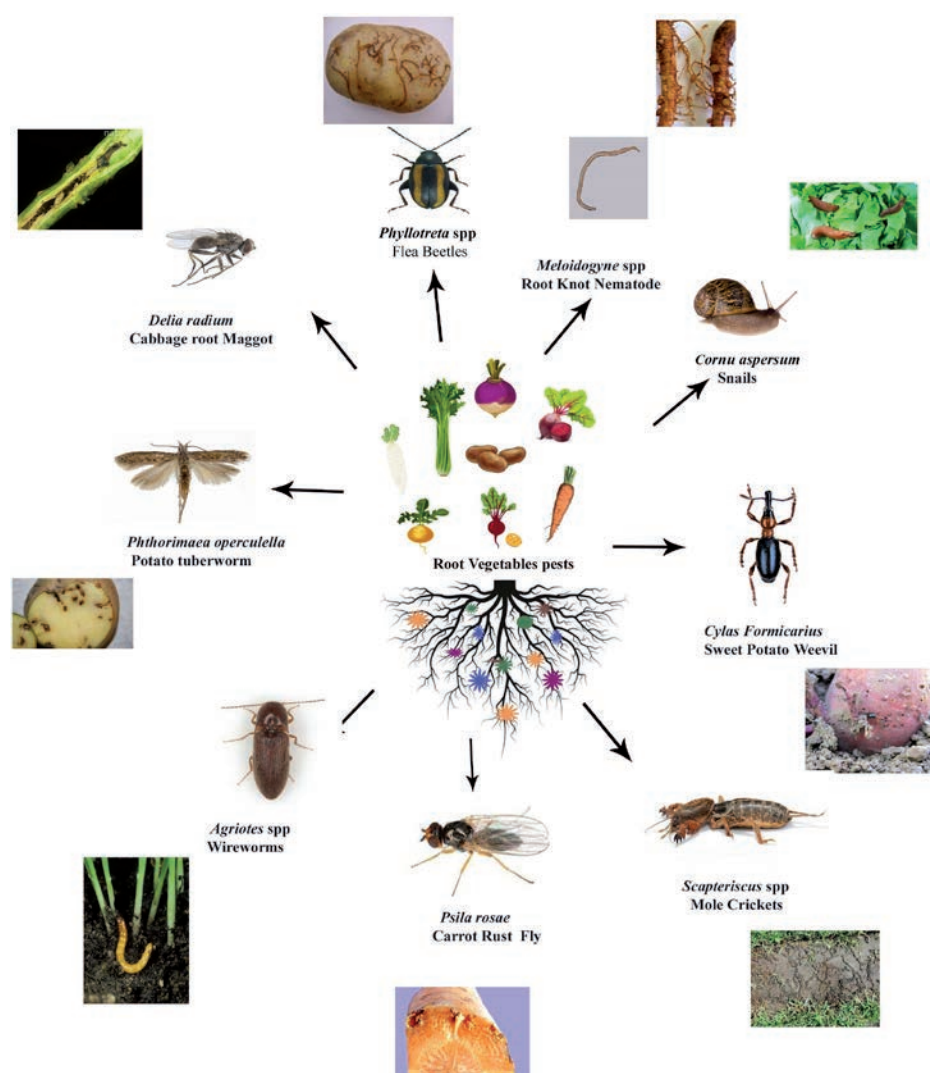


Figure 2.
 Root vegetable pests and their diseases.

variations need integrated pest management (IPM) strategies [25, 47] that leverage natural controls, including biofumigation, resistant cultivars, and microbial biocontrol agents (Figure 2) [53].

2.3 Behavioral patterns of the root vegetable pests

Root vegetable pests exhibit a variety of behaviors that influence their feeding activities, like chewing, burrowing, and piercing-sucking habits among pests [45]. Mobility- and host-selection-based strategies [51]: some pests aggressively burrow through soil in search of hosts, while others use chemical signals to identify suitable plants [25, 47]. Environmental factors such as light, temperature, and humidity influence the behavioral activities of pests [40, 43]. These behavioral features are

critical to pest survival, reproduction, and spread, thus rendering them important predictors of infestations and effective methods for controlling them [41, 44], such as circadian cycles of the nematodes and seasonal variations also influence pest behavior [54].

By understanding the biological cycle, physiological adaptations, ecological and behavioral patterns, farmers can easily manage the pest population using barriers to disrupt the pest-host interaction [52, 53].

3. Rhizopathological constraints in the root vegetables: Fungal, bacterial, and viral diseases and symptoms

Root vegetables are also severely affected by pathogenic infections, which cause wilting, root rot, discoloration, structural abnormalities, and major output losses [55]. These diseases also harm plant health by interfering with nutrient uptake, compromising cellular integrity, and hastening post-harvest degradation, resulting in lower market excellence and customer acceptance [56]. In the following discussion, we will look at different diseases that affect these crops and explore appropriate diagnostic and preventive actions to ensure their safety and sustainability.

3.1 Major fungal diseases and symptoms affecting the root vegetables

Fungal infections are among the most persistent dangers to root crops because these infections are frequently favored by high humidity, poor drainage, and prolonged wetness conditions [55, 56]. Major fungal infections that mostly affect root vegetables, *Pythium* spp., are pathogens that thrive in moist soils and are known to cause *Pythium* Root Rot, which appears as soft, water-soaked sores on roots and can cause damping-off in seedlings [57]. *Plasmodiophora brassicae* Woronin, which causes clubroot disease, is another noteworthy pathogen that affects cruciferous plant roots, resulting in swollen, distorted roots and wilted foliage [58]. *Fusarium* spp. are also of concern because they cause Fusarium Root Rot disease, which affects root vegetables, having wilting and root dry rot symptoms [59]. *Thielaviopsis basicola* (Berk. and Broome) Ferraris causes Black Root Rot, result in black discoloration of roots, restricted growth, and leaf chlorosis [60]. Furthermore, *Rhizoctonia solani* J.G. Kuhn causes *Rhizoctonia* Root Rot, which is a soil-borne fungus that lives as sclerotia (hardened fungal structures) and infects plant roots [61]. All these pathogens substantially influence plant health and food quality of root vegetables (Figure 3) [56].

3.2 Major bacterial diseases and symptoms affecting root vegetables

Root vegetables are susceptible to numerous bacterial diseases. The growth and productivity of root vegetables are substantially influenced by these pathogenic bacteria, which significantly affect their yield and quality. Major bacterial pathogens that is, *Pectobacterium carotovorum*, affecting root vegetables, causing soft rot disease, water-soaked lesions, tissue softening, and cavity formation due to cell wall degradation [62, 63]. *Dickeya dadantii* causes watery, foul-smelling rotting in root vegetable crops [63]. *Ralstonia solanacearum* causes Bacterial Wilt, showing

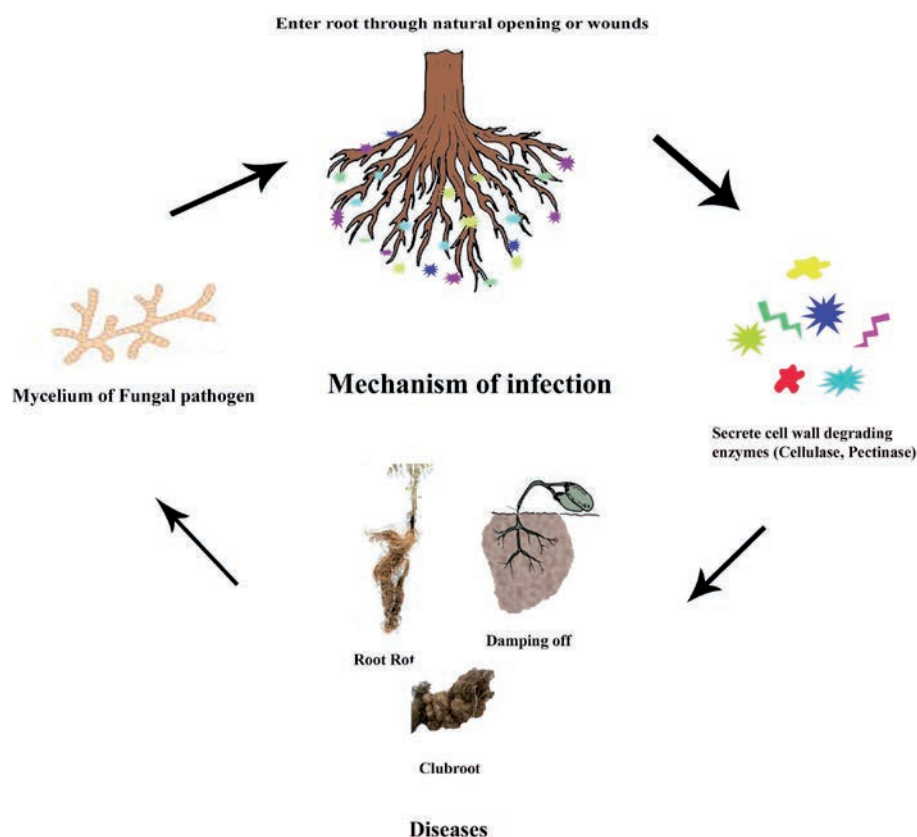


Figure 3.
 Fungal mechanism of infection.

wilting, vascular browning, and root degradation symptoms. Scab disease [64], caused by *Streptomyces scabies*, appears as rough, scabby lesions on the root surfaces [65]. *Agrobacterium tumefaciens* Conn 1942 causes Crown Gall disease [66]. *Xanthomonas campestris* Dowson 1939 causes swollen, tumor-like galls to appear on the roots and stems of many root vegetables [67]. These bacterial diseases not only reduce agricultural production but also threaten the shelf life of root vegetables (Figure 4).

3.3 Major viral diseases and symptoms affecting root vegetables

Root vegetables are also vulnerable to a variety of viral infections, which have a substantial impact on the quantity and quality of food. Carrot Motley Dwarf disease is commonly caused by *carrot red leaf virus* (CtRLV) and *carrot mottle virus* (CMoV), which exhibit growth stunting and leaf reddening in carrots, resulting in reduced root size and low quality [68, 69]. *Necrotic yellow vein virus* (BNYVV) affects sugar beets, resulting in vein yellowing, root deformation, and stunted growth, lowering sugar quantity and production of crops [70]. *Turnip mosaic virus* (TuMV) infects cruciferous root vegetables, having mosaic patterns on the leaves, necrotic lesions, and root malformations that reduce their commercial value [71, 72]. *Beet curly top virus* (BCTV) inhibits beet and turnip growth, causing

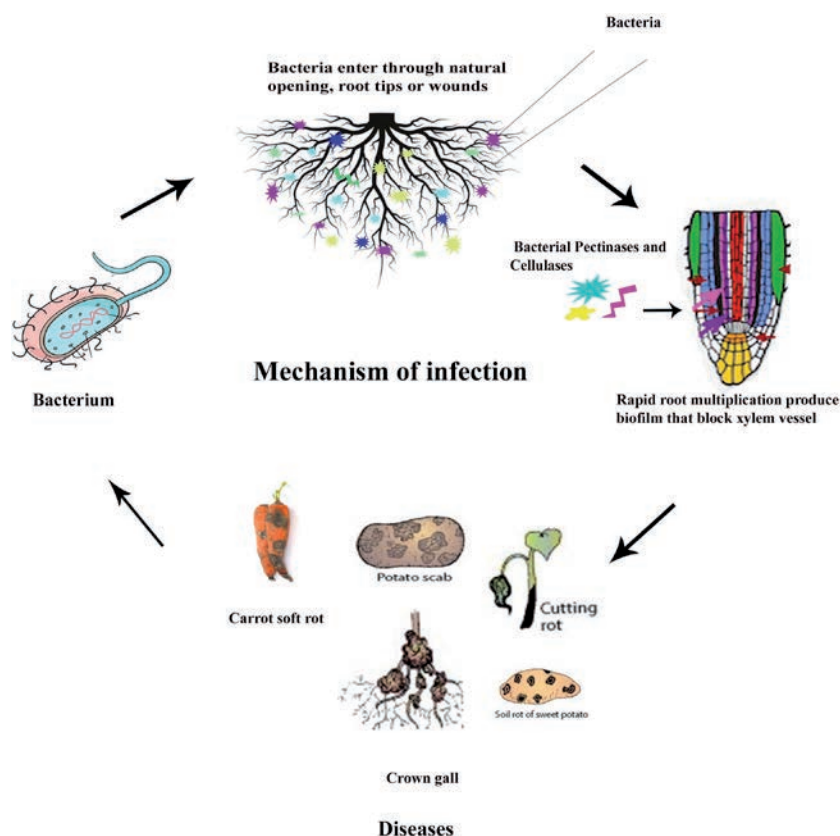


Figure 4.
Bacterial mechanism of infection.

leaf curving, thickness, and root abnormalities that render the vegetables unsalable (Figures 5–7) [73].

3.4 Epidemiology and transmission dynamics of soilborne pathogens

Pathogens that harm root crops are spread by many kinds of environmental factors, including humidity and pH, temperature variations, and the presence of organic matter, which promote pathogens to infect hosts and multiply [74]. Transmission occurs when the susceptible plant roots come into contact with contaminated soil, infected plant debris, drainage, vectors, and plant-to-plant interactions, resulting in increased disease incidence and severity in sensitive crops [75]. Insect vectors, nematodes, and fungal carriers contribute to the spread of bacterial, viral, and fungal diseases [76]. Understanding these transmission dynamics is critical for establishing successful disease management measures to reduce the pathogen attacks and prevent further disease outbreaks [77].

3.5 Agronomic and economic consequences of soil-borne pathogens

These plant diseases pose significant agronomic and economic issues by reducing the yield, quality, and market value [78]. Soil-borne fungus *Verticillium dahliae* leads to severe economic concern in root vegetables such as lettuce and

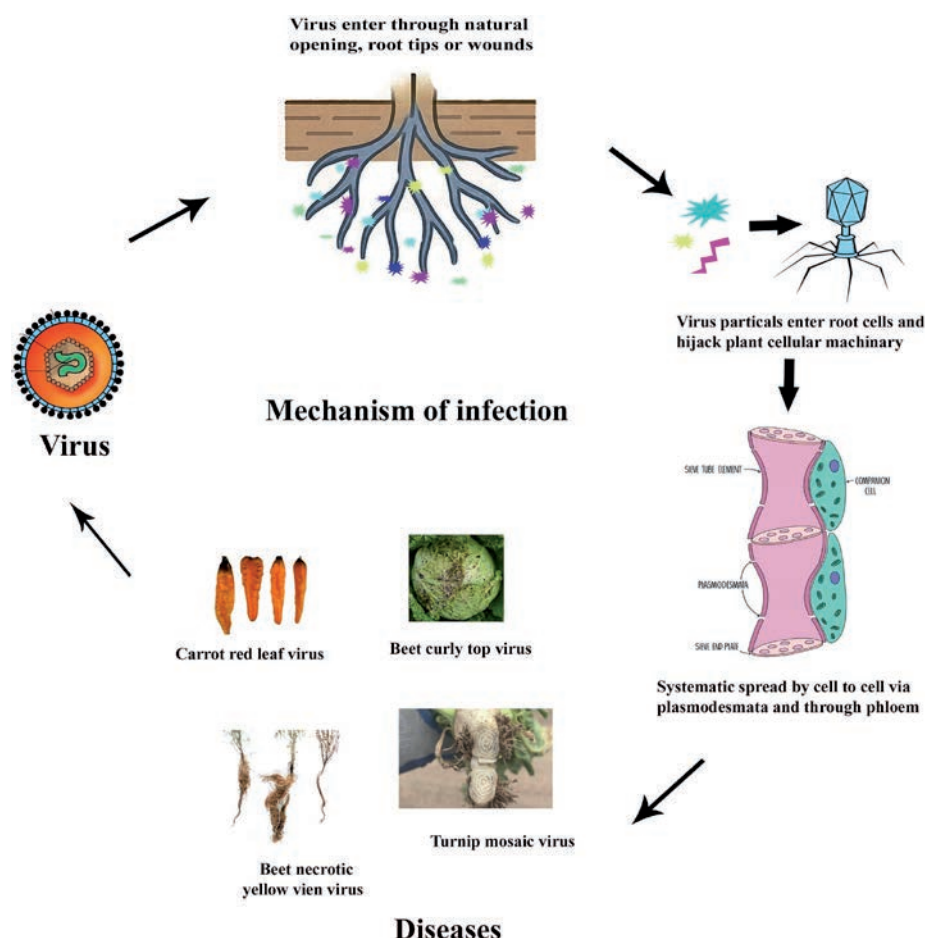


Figure 5.
Viral mechanism of infection.

potatoes in California, causing pre- and post-harvest losses [79]. According to the global assessments, pathogens and pests cause extensive yield loss across major potato crops, up to 17.2% [78]. The National Clean Planting Network (NCPN) in the U.S. reveals that pathogen-tested propagation materials yield high economic returns (10:1–150:1), reducing long-term losses in root vegetable crops [80]. In some countries that rely on root vegetable agriculture, widespread infections may compromise food security, disrupt supply chains, and limit export possibilities, making effective disease management a top concern for sustainable agricultural production [78].

3.6 Advanced diagnostic strategies for the soilborne pathogens

Advanced diagnostic methods for fungal, bacterial, and viral diseases in root vegetables include molecular, serological, and imaging approaches to detect pests, such as root-knot nematodes [40], bacterial soft rot [81], viral [82], and fungal diagnosis [55]. Polymerase chain reaction (PCR) and quantitative PCR (qPCR) are commonly used to accurately identify fungal and bacterial infections by targeting

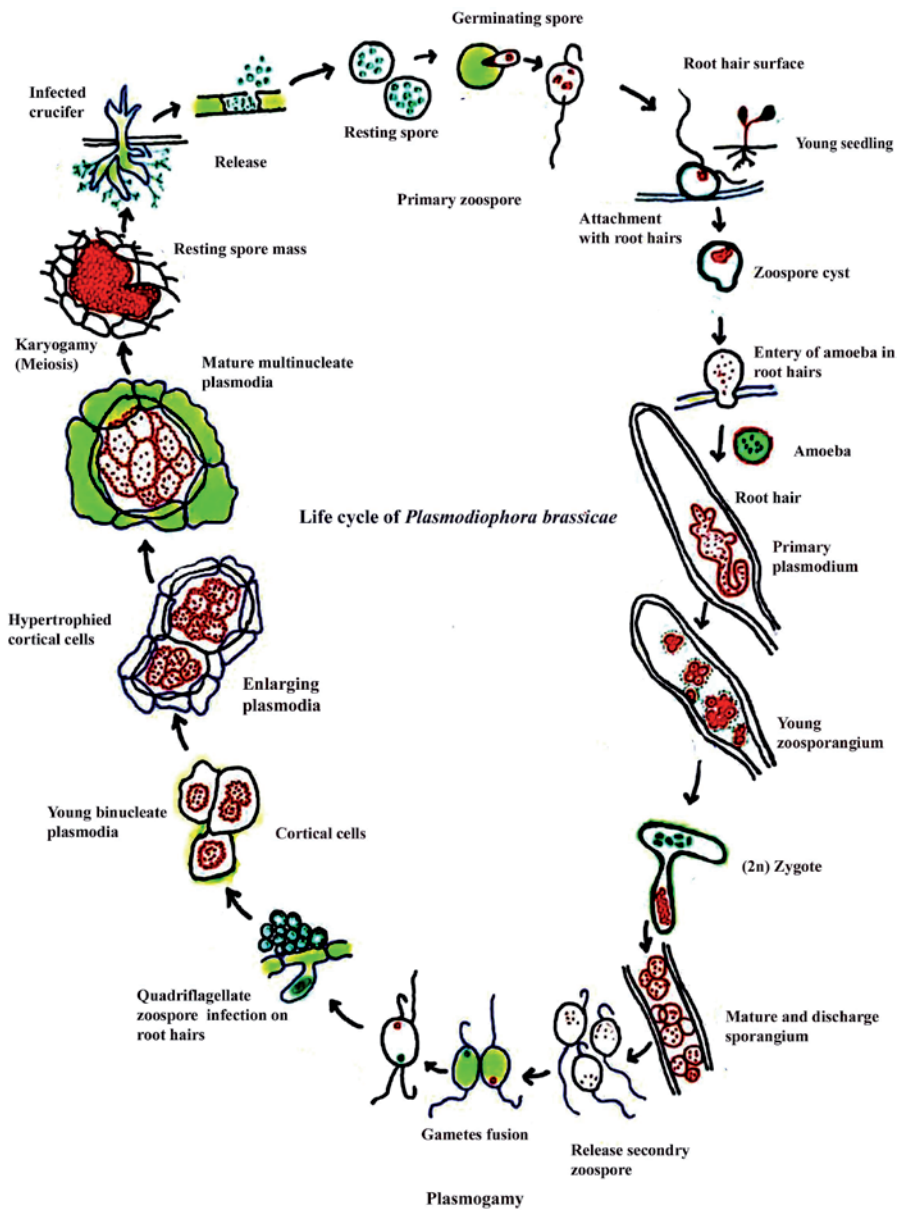


Figure 6.
Life cycle of Plasmodiophora brassicae.

species-specific genetic markers, whereas reverse transcription-PCR (RT-PCR) is used to detect viral RNA, DNA, and RNA-based probe development. Next-generation sequencing (NGS) molecular methods are effective in disease control for both culturable and unculturable pathogens [83]. High-throughput sequencing (HTS) and metagenomic methods (biosensors, spectroscopy, and hyperspectral imaging) improve disease surveillance by identifying new or emerging pathogenic strains [84, 85].

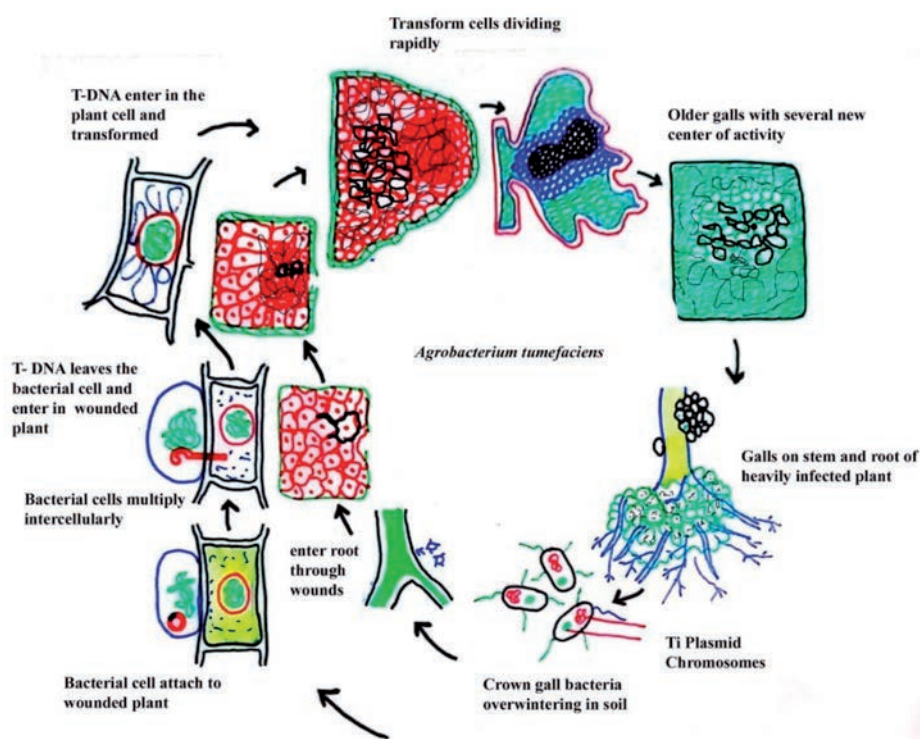


Figure 7.
 Life cycle of *Agrobacterium tumefaciens*.

4. Various integrated control strategies to protect root vegetables

Managing diseases and pests in root vegetable crops requires an intricate strategy that includes various control measures [86]. Various genetic resistance approaches identified quantitative trait loci associated with resistance by accessing the whole genome [87]. Integrated Pest Management (IPM) ensures a comprehensive, science-based approach to pest and disease control [88]. These strategies address the complex interactions among soilborne diseases, insect vectors, and environmental conditions that influence disease dynamics [89, 90]. Various control methods such as biological [91], physical, chemical [92], and organic alternatives [93] are used to manage the root infections. By combining these scientifically verified measures, we can effectively safeguard root vegetable crops through spectroscopic studies [92, 94], increase resilience against emerging diseases, and maintain long-term agricultural productivity in the face of global concerns like climate change and soil degradation [95].

4.1 Cultural controls: Modifying root vegetables production practices to prevent pests and diseases

4.1.1 Soil health management

Soil health is essential for optimal root vegetable production, as it affects both plant health and the prevalence of pests and diseases [96]. Crop rotation, and soil

amendments by the addition of organic and inorganic materials (compost and biochar) resulting healthier rhizosphere [97], pH adjustment (such as *Fusarium* and *Pythium*, often thrive in acidic soils) [98], and mulching that involves applying a layer of material (organic or synthetic) to the soil surface surrounding the plants [93, 99]. Soil health practices impact the lifecycle of crop-specific pests and diseases, lowering their population density in the soil. These practices also enhance soil nitrogen cycling, reducing the danger of soil deterioration and which benefits the root vegetable crops [100].

4.1.2 Seed and planting strategy

Seed and planting practices are fundamental for reducing disease risk, establishing healthy crops, and optimizing root vegetable yield potential. For example, using disease-resistant varieties of carrots can help to prevent *Fusarium* wilt and *Alternaria* leaf blight diseases [54]. Certified seeds and tubers are guaranteed to be disease and pest free thanks to rigorous testing and quality control standards established by seed certification bodies [101]. Proper plant spacing and adjusting their planting dates to avoid periods of pest activity are important for reducing disease risk. These practices optimize airflow, sunshine exposure, and root development while reducing pathogens' mobility between plants [102].

4.1.3 Water management for the root vegetables

Water management is very important for reducing the risk of diseases and insect infestations in root vegetables [97]. By reducing over-watering and monitoring the soil moisture level [98, 100], drip irrigation delivers the water more precisely to the plant's root system, fostering healthy root development and improving nutrient absorption [91, 99, 103]. Making sure the soil is well-drained allows excess water to be swiftly evacuated, keeping the roots from becoming soggy. Well-drained soils give adequate oxygen levels to the root zone, promoting root growth and increasing plant resistance to diseases, that is, Root rot, *Fusarium* wilt, and bacterial soft rot [93]. Soilless farming practices help to grow root vegetables more effectively than traditional soil-based methods that provide the soil-based-pest free environment. It saves water (990%), fertilizer (75%), and land (75%), which is important in dry land by providing higher crop yields, about 147.3 tons per hectare more than soil farming [100].

4.2 Biological controls: Modifying root vegetables production practices to prevent pests and diseases

Biological management, unlike traditional chemical treatments, depends on natural creatures such as beneficial microorganisms, *Trichoderma harzianum* Rifai, 1969, and *Bacillus subtilis*, as well as natural predators like nematodes, ladybirds, parasites, and root vegetable pests to contribute to long-term pest suppression [104].

4.2.1 Beneficial microorganisms

The use of eco-friendly microbes is magnificent for treating a wide range of soil-borne pests [105], particularly through beneficial nematodes such as *Steinernema* spp. and *Heterorhabditis* spp., and *Steinernema parasitises* wireworms and mole crickets, releasing toxins that ultimately kill them [106, 107]. Control of fungal diseases in

root vegetables primarily relies on beneficial fungi such as *Trichoderma* spp. and Arbuscular Mycorrhizal Fungi (AMF) [104]. Beneficial bacteria, such as *B. subtilis*, *B. thuringiensis* (BT), produce toxins lethal to certain insect larvae, and *Pseudomonas fluorescens*, which can prevent the growth of bacterial and viral pathogens [82, 108].

4.2.2 Predatory insects and arthropods

The introduction of lady beetles (Coccinellidae), lacewings (Chrysopidae), and ground beetles (Carabidae) that feed on root maggots, wireworms, and parasitic wasps (*Aphidius* spp.) aids in aphid population control to suppress viral infections [106]. Similarly, for bacterial diseases that frequently exploit insect-inflicted wounds to infect plants, predatory mites (*Amblyseius* spp.) and rove beetles (*Staphylinidae*) help by preying on small insects such as thrips and whiteflies [109]. Parasitoids like *Trybliographa rapae* feed on the larvae of the cabbage root flies and reduce their survival rates significantly [110]. Entomopathogenic fungi, including *Metarhizium anisopliae* and *Beauveria bassiana*, infect by penetrating the outer cuticle walls and killing soil-dwelling pests. When it comes to pest control, predatory arthropods effectively prey on them [111]. By fostering these natural predators in agricultural ecosystems, and enhancing plant resilience against viral, bacterial, fungal, and pest-related threats in root vegetable crops [112].

4.2.3 Pathogen suppressive plants

Plants that inhibit pathogens help to prevent viral, bacterial, and fungal diseases in root vegetable crops by producing bioactive substances and increasing beneficial soil microorganisms. Marigolds (*Tagetes* spp.), garlic (*Allium sativum* L.), and mustard (*Brassica* spp.) discourage aphid vectors, limiting the transmission of viruses such as (CtRLV) and (TuMV) [107, 108]. Plants like neem (*Azadirachta indica* A. Juss.), basil (*Ocimum basilicum* L.), mustard (*Brassica juncea* (L.) Czern.), and rye (*Secale cereale* L.) have natural fungicidal chemicals [109].

4.2.4 Viral control using biological agents

Aphid parasitoids such as *Aphidius colemani* and *Aphidius ervi* aid in the management of aphid populations, decreasing the transmission of viruses, such as (CtRLV), (CMoV), and (TuMV) in root crops [108]. Furthermore, biocontrol viruses such as baculoviruses attack insect pests, including wireworms, root-knot nematodes, and mole crickets, minimizing crop damage and limiting entrance routes for bacterial and fungal illnesses [112]. Potato virus Y (PVY) can be effectively managed using various strategies such as oil spraying, straw mulching, and intercropping [113].

4.3 Physical and mechanical controls to manage root vegetable diseases and pests

Physical and mechanical control strategies are critical for managing diseases and pests in root crops because they limit the pathogen spread and reduce insect populations without depending on other treatments. The role of row covers and strip tillage in defending against the insect vectors that carry these viruses [114], and suppresses root-knot nematodes [115]. Michigan State University Extension suggested that tillage practices play an important role in disrupting soilborne pathogens [116] by exposing them to unfavorable conditions, aerating the soil [117].

4.4 Organic and natural remedies for root vegetable health

Organic and natural metabolites are environmentally benign alternatives to synthetic chemicals, making them perfect for sustainable farming. Vego Garden uses Diatomaceous earth [118] as a natural pesticide that dehydrates and kills soft-bodied pests such as wireworms and root-knot nematodes [119, 120] while protecting beneficial creatures [121]. Fine garden practices use garlic and chili sprays as natural repellents that prevent pests like mole crickets [122, 123]. Compost tea [124], mineral oils that contain beneficial bacteria, improve soil health and develop plant immunity [125].

4.5 Chemical control: Targeted applications to manage pests and diseases in root vegetables

Chemical management is used as a last remedy to manage viral, bacterial, and fungal diseases, as well as pest infestations in root vegetable crops, when conventional cultural, biological, and physical measures fail to give enough protection [126, 127]. Chemical treatments such as insecticides, fungicides, bactericides, and nematocides provide quick and effective disease and pest control [128]. Synthetic pyrethroids (λ -cyhalothrin) and insecticides, including imidacloprid, thiamethoxam, cyantraniliprole [129], and fipronil, are frequently used to control wireworm populations [130]. Nematicides such as fluopyram, fosthiazate, and oxamyl are used to control nematode infestations in the soil [98, 103]. Insecticides such as bifenthrin, fipronil, and carbaryl are used to manage mole crickets and are frequently administered as granular formulations to target both larvae and adults [131, 132]. Commonly used broad-spectrum fungicides include metalaxyl for (*Pythium*) [133], azoxystrobin, thiophanate-methyl (*Fusarium*) [134], and fluazinam (*Plasmodiophora* clubroot) [135]. To restrict bacterial development in root vegetables, copper-based bactericides (copper hydroxide, copper sulfate) [136], and antibiotics such as streptomycin are used [137, 138]. Viruses cannot be treated directly with chemicals; chemical control focuses on controlling insect vectors [62], such as aphids that propagate the viruses. Insecticides such as imidacloprid and pyrethroids (λ -cyhalothrin) are frequently used to suppress aphid populations and reduce virus transmission [139, 140].

5. Case study suggestions

5.1 Managing the potato late blight disease: A case study from Ireland

Potato Late Blight, produced by the class oomycetes *Phytophthora infestans* (Mont.) de Bary, is one of the most destructive plant diseases in agricultural history. *P. infestans*' historical significance is inextricably linked to the Great Irish Famine (1845–1852), when recurrent crop failures owing to late blight caused widespread famine and mass emigration, resulting in a severe socioeconomic and demographic impact on Ireland [141]. Potatoes produce 400 million tons per year and play a pivotal role in food security. The Irish experience with potato late blight was a significant milestone in plant pathology, as it prompted the creation of disease management measures. Early epidemiological research and advances in fungicide treatments were started. Today, understanding the biology and control of *P. infestans* is crucial for modern root vegetable cultivation, as climate change and evolving pathogen strains continue to threaten global food security [142]. Sustainable measures, including resistant

cultivars, integrated pest management (IPM), and improved forecasting models, are critical to reducing the disease's impact on global potato production [143].

5.2 Disease epidemiology and impact

Ireland's marine climate, with regular rains and mild temperatures, provided a perfect environment for the rapid development of late blight [142]. Thrives in cool, humid environments with ideal temperatures of 10–20°C and high humidity levels, rapidly infecting potato foliage and tubers, resulting in severe yield losses [141]. Its aggressive nature and ability to spread quickly *via* windborne spores make it an ongoing concern for potato growers globally [144]. The famine demonstrated the vulnerability of monoculture systems and the need for diverse cropping and robust disease management techniques to ensure food security. In modern times, disease outbreaks continue to threaten potato production in Ireland [145].

5.3 Diagnosis of the disease late blight in potatoes

Accurate and fast detection of potato late blight, caused by *P. infestans*, is critical for effective disease treatment and crop loss. Traditional diagnosis approaches rely mostly on field observations, with the first symptoms appearing as small, light to dark green, circular to irregularly shaped, water-soaked spots on the leaves. Laboratory techniques such as quantitative Polymerase Chain Reaction (qPCR) [76, 146] molecular diagnosis [147], and enzyme-linked immunosorbent assay (ELISA) are advanced, making it easier to detect and are used to identify *P. infestans* [148, 149].

5.4 Control measures and disease management approaches

Potato late blight (*P. infestans*) requires a multimodal approach that combines chemical, biological, and cultural measures to reduce disease burden and promote sustainable agriculture. In 2018, Ireland experienced one of the worst outbreaks of the late Blight in recent history. All the traditional fungicides became less effective due to pathogen resistance, leading to a 40% decrease in yield in affected areas [145]. Preventing potato late blight requires a complex approach that includes resistance breeding and modern genetic engineering approaches. Effective cultural practices are critical in preventing late blight outbreaks [150]. Furthermore, the DuRPh project (2006–2015) cisgenic potatoes were developed by inserting only potato resistance (R) genes. These field trials show 80% strong resistance against late blight disease with less fungicide use [151], promoting sustainable farming and ensuring the public acceptance of cisgenesis. In Poland and Ethiopia, various studies have been conducted related to the improved organic-based farming system to improve yield and choose different varieties to check the right one with fungicide based on the variety-specific disease resistance and yield, respectively [152–154]. The use of helpful microorganisms provides an environmentally favorable alternative to conventional fungicides. *Trichoderma* and *Bacillus* have shown antagonistic effects against *P. infestans* [155]. For example, *B. velezensis* strain AFB2-2 has been proven to effectively inhibit late blight in organic potato farming [150]. This strain has been shown in studies to impede the mycelial growth of *P. infestans* and reduce disease incidence in field circumstances, making it a suitable biocontrol agent. Adoption of such biological controls can reduce dependency on chemical inputs while promoting environmental sustainability [156], by controlling the various environmental factors that affect the disease severity [157].

5.5 Lessons learned in disease surveillance and future perspective

Midway through the 1800s, the Irish Potato Famine served as a catastrophic reminder of the risks of agricultural monocultures and the lack of genetic diversity among major crops. A single potato type that was widely grown and infected with *P. infestans* was the cause of the famine, which led to dramatic crop failures and widespread starvation. Adaptive strategies, like as altering planting dates, can mitigate the initial rise in late blight risk that some locations may encounter, according to studies. For instance, moving farming to the cooler months has been suggested as a way to lower disease prevalence. To avoid future agricultural practices, it is essential to support breeding activities aimed at creating potato cultivars resistant to disease and climate change to prevent future agricultural disasters.

6. Integrated pest management of the sweet potato weevil in Africa

6.1 Introduction

The sweet potato weevil (*Cylas formicarius*) is a major pest in sweet potato (*Ipomoea batatas*) agriculture, especially in Africa. This bug offers a significant threat to sweet potato production since it can inflict severe damage to both store roots and vines [158]. Infestations can cause output losses ranging from 20 to 50% on many farms, with other reports estimating losses of 73–100% in specific African locales [159]. The sweet potato weevil has a significant economic impact in Africa. According to NC State University in 2019, severe weevil infestations not only lower commercial crops but also threaten food security and farmer livelihoods [160, 161].

6.2 Biology and impact of the sweet potato weevil

Weevils lay eggs in stem fissures or directly on tubers, and when the larvae hatch, they dig into the plant, tunneling through stems and roots, causing extensive damage [158, 162]. Infestation causes stunted growth, wilting, and root tunneling, which can make tubers bitter and unmarketable due to secondary fungal infections [159]. Nigeria, Uganda, Ghana, and Kenya are among the most afflicted African countries, where warm temperatures and high humidity promote rapid weevil multiplication [160]. Furthermore, genetically modified sweet potatoes with insect resistance have been investigated as a sustainable alternative, particularly in Kenya [161].

6.3 Diagnosis and early detection methods

Early and accurate detection of sweet potato weevil is critical for successful control and prevention of large-scale infestations. Infested sweet potato plants have stunted growth, leaf wilting, and typical root tunneling [158]. Another significant symptom is the presence of larvae inside tubers, which bore through the roots, leaving behind frass-filled galleries that cause secondary fungal and bacterial infections [159]. In several African regions, farmers include locally tailored pheromone-based monitoring systems within their Integrated Pest Management (IPM) methods [160].

6.4 Prevention strategies for integrated pest management (IPM)

To effectively manage sweet potato weevil, an Integrated Pest Management (IPM) approach integrating cultural, physical, and biological techniques is required. These strategies aim to reduce weevil populations, minimize invasion, and avoid pathogenic spread in the sweet potato-growing region [163]. Crop rotation with non-host plants helps to limit continuous population growth, making it more difficult for weevils to locate suitable hosts [31]. The removal and destruction of contaminated plant leftovers promptly upon harvest prevents the next generation of weevils from completing their life cycle [164–166]. Field applications have shown that it reduces weevil populations by infecting and killing larvae on contact. Entomopathogenic Nematodes, *Steinernema* and *Heterorhabditis*, have shown promise in controlling sweet potato weevil invasion [167]. Neem oil is derived from the neem tree (*Azadirachta indica*) and has been studied for its insecticidal abilities against sweet potato weevils [163]. Natural pyrethrins, derived from chrysanthemum flowers, have been recognized as effective and environmentally friendly insecticides for controlling *C. formicarius* adults [167]. To prevent the development of resistance, these insecticides can be used sparingly and in conjunction with other control strategies [168].

6.5 Future challenges and recommendations

Climate changes present a substantial problem to root vegetable crops, as rising temperatures and shifting rainfall patterns influence pest distribution and severity. Furthermore, encouraging cost-effective and farmer-friendly Integrated Pest Management (IPM) strategies to ensure long-term agricultural development. Sustainable pest management is critical for root vegetable production and food security, and future initiatives should focus on increasing IPM adoption, enhancing farmer education, and utilizing biotechnology to reduce pest risks. Scientists, agriculturists, academicians and policy makers should work in collaboration to develop effective control strategies for root vegetables.

7. Conclusion

To ensure long-term root vegetable cultivation, farmers must implement an integrated pest and disease management approach. Crop rotation, appropriate plant spacing, and soil healthcare can be combined with biological controls such as beneficial predators and biopesticides, as well as precision agricultural techniques, to provide a comprehensive and resilient approach to control the major root vegetable diseases. Strategic chemical use, given only when essential, can help to improve this system without harming the environment. Future advances, such as genetically engineered biological control agents, real-time monitoring devices, and environment-friendly herbicides, will let farmers respond to shifting pest infestations. Early discovery, prevention, and management will be important to crop protection. Farmers may establish a resilient farming system by embracing biodiversity, improving natural plant resistance, and minimizing environmental stressors. The integration of these innovations into everyday practices will not only boost yields and crop health but also secure long-term sustainability for global agriculture.

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Author details

Muhammad Aijaz Ahmad* and Ifra Aslam
Institute of Botany, University of the Punjab, Lahore, Pakistan

*Address all correspondence to: aijazbotanist@gmail.com

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Micronutrients for Production and Biofortification of Cassava

Alysson Roberto Baizi e Silva

Abstract

Micronutrients are strategic elements for increasing the production of crops and improving the quality of harvested products. Despite this, they have been neglected in cassava (*Manihot esculenta* Crantz), one of the most important root vegetables in the tropics. This chapter aims to show how micronutrients can increase yield and improve nutritional quality of cassava. Research results covering the influence of micronutrients on yield and biofortification of roots of the plant are reviewed in detail. Boron, Cu, Mn, or Zn fertilization can increase root yield. Genetic biofortification is efficient in increasing Fe and Zn concentrations in cassava roots. The increase in Zn concentration can also be achieved by agronomic biofortification. A combination of genetic and agronomic strategies to biofortify cassava needs to be studied. In addition, further studies are needed to establish criteria for the large-scale application of micronutrient fertilizers in cassava. Use of genetically biofortified cultivars and judicious application of micronutrients are essential to increase production and improve the nutritional quality of cassava and thus ensure food security in the tropics.

Keywords: boron, copper, fertilization, iron, manganese, *Manihot esculenta*, mineral nutrition, root crop, zinc

1. Introduction

Plants require 14 mineral nutrients to grow [1]. These nutrients are divided into macronutrients and micronutrients. The macronutrients comprise nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). The micronutrients include boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn). The difference between these two classes of nutrients is in the amount required by plants. Macronutrients are required in large amounts, and micronutrients in small amounts. Despite their lower requirement, micronutrients are as important as macronutrients for plant growth. However, little attention has been given to micronutrient nutrition in some crop plants. One of these plants is cassava (*Manihot esculenta* Crantz).

Macronutrient nutrition of cassava has been extensively studied [2]. On the other hand, there are few studies on its micronutrient nutrition [3]. The reasons for this scarcity of studies have not been determined yet. Nonetheless, some causes are suggested here. The first is the focus of research on N, P, and K nutrition, probably motivated by the high cost of fertilizers used to provide these nutrients for the crop.

The second is the assumption that the high colonization of cassava roots by mycorrhizal fungi observed in several studies [4–6] is sufficient for the acquisition of the amounts of micronutrients required by the plant. The third is that cassava cultivation is predominantly carried out in very acidic soils where there is higher availability of micronutrients and thus greater capacity to meet the plant's needs. The fourth is the low demand of farmers for research with micronutrients, since they have little knowledge about the effects of these nutrients on the plant.

However, studies on micronutrients in cassava have increased in recent years, probably due to the need to better understand the role of such nutrients in the production of this crop. Another reason is the interest in biofortifying cassava with micronutrients, particularly with Fe and Zn. Biofortification refers to the increase in micronutrient concentration in the edible parts of food crops through breeding or fertilization [7–9]. Both strategies have been successfully used to biofortify cassava root, which is the main edible part of the plant [10, 11]. Thus, productive and nutritional aspects have motivated research on micronutrients in the crop.

Cassava is an essential vegetable crop for food security in the tropics. It is estimated that this crop contributes to the nutrition of more than 800 million people distributed mainly in South America, sub-Saharan Africa, and Asia [12, 13]. It is also strategic to strengthen agriculture as a livelihood in rural areas [14] and to produce food in an uncertain agricultural scenario due to climate change [15]. In this context, micronutrients can play an important role in the production and biofortification of cassava, providing nutritious food in sufficient amounts to help feed future generations.

This chapter aims to show how micronutrients can increase yield and improve the nutritional quality of cassava.

2. Responses to micronutrients

An overview of micronutrients in soils and plants is provided for B, Cu, Mn, and Zn, including total and available concentrations in soil, uptake, and functions in plant growth. In the sequence, symptoms and critical concentrations of deficiency and toxicity as well as responses of cassava to fertilization are provided.

2.1 Boron

The total concentration of B in the surface layer of tropical acid soils is quite variable. Surveys carried out in some municipalities of Brazil, for example, show a variation from 10 to 38 mg kg⁻¹ [16, 17]. The concentration of hot water soluble B, which is a measure of B availability to plants, also varies greatly in Brazil, ranging from 0.01 to 10.6 mg dm⁻³ for soils of the estate of São Paulo and from 0.01 to 8.25 mg dm⁻³ for soils of other Brazilian states, with relatively low mean and median values (0.32 and 0.23 mg dm⁻³ and 0.31 and 0.24 mg dm⁻³, respectively) [18]. Low concentrations of soluble B in soils restrict the absorption of B by plant roots.

Boron is absorbed from the solution of acid soils as undissociated boric acid (H₃BO₃) and its uptake rate is influenced by several factors, including (i) external concentration of B and other elements, (ii) soil pH, (iii) soil moisture, as well as (iv) characteristics of root system, (v) growth stage, (vi) transpiration and (vii) nutritional status of plants [19, 20]. For cassava, B uptake was shown to be also dependent on the temperature in the root zone, being higher in the range from 26 to 33°C [21].

Once absorbed, B is transported *via* xylem to organs that are growing rapidly. Boron can also be remobilized to other organs, but only in some plant species, where it is mobile in the phloem [22]. In most species, however, B is immobile in the phloem [22], and thus it cannot be remobilized. Cassava is included in this last group of plants, where B is immobile in the phloem [23]. Because of the B immobility, symptoms of B deficiency appear first in younger leaves, and those of B toxicity in older leaves.

The functions of B in plants are not well understood yet. However, it is well accepted that the primary role of B is to stabilize the cell wall structure [24, 25]. Other roles would be secondary and linked to the primary role. Secondary roles include (i) plasma membrane integrity and function, (ii) phenol and phytohormone metabolism, (iii) root elongation and shoot growth, and (iv) formation and viability of reproductive structures [25]. Boron can also improve important processes within the plant such as photosynthesis and water use [26–32]. When the supply of B is insufficient, these functions are impaired, and deficiency symptoms, reduced growth, and loss of yield may occur in plants.

Symptoms of B deficiency in cassava were described for the first time by Krochmal and Samuels [33]. Plants grown in sand culture without added B were dwarfed in the initial stages of growth, and younger leaves were slightly chlorotic and reduced in size. However, plant height and fresh weight of shoot were not affected by the deficiency. Later, Forno et al. [21] expanded the description of symptoms for plants grown in solution culture. The first symptoms reported by the authors occurred in the root system. The roots of B-deficient plants were short, swollen at the tip, and often blackened. At the plant top, symptoms included sequentially stunted growth, shortened internodes, younger leaves reduced in size, curved sideways, and with fine chlorotic spots, as well as longitudinal cracks on the stem and petioles. Finally, dry matter yields of tops, roots, and whole plants were drastically reduced by B deficiency. Although the critical concentration for B deficiency could not be calculated precisely in this study, the authors suggested that it would be around 17 mg kg^{-1} at the top of plants with 40 days of growth. Subsequently, Howeler et al. [34] accurately determined the critical B deficiency concentration in the youngest fully expanded leaf (YFEL) blades of plants grown in solution culture for 9 weeks, obtaining a value of 35 mg kg^{-1} . Concentrations below 17 mg kg^{-1} at the plant top or 35 mg kg^{-1} in YFEL blades indicate B deficiency in young plants. Boron deficiency in field-grown cassava does not seem to be as uncommon as reported in the literature [34], since it has occurred in Colombia, Vietnam, and China [35]. In areas subject to deficiency, the crop may respond to B application.

Field experiments conducted to determine cassava responses to B application are reduced in number but distributed in different parts of the world. In Australia, application of up to 3.6 kg B ha^{-1} to a soil replaced after bauxite mining did not significantly affect root yield [36]. In this study, B concentration in fully expanded leaves ranged from 22 to 38 mg kg^{-1} . On the other hand, positive and significant responses were obtained in an experiment in Thailand [37]. Some results of this study are shown in **Table 1**. Application of 1 kg B ha^{-1} as boric acid to an Ultisol increased the fresh tuberous root yield regardless of Ca supply. The highest yield (36.8 t ha^{-1}) occurred in combination with the application of $400 \text{ kg Ca ha}^{-1}$. This combination also resulted in a high yield of starch (10.1 t ha^{-1}) and a concentration of B in YFEL (21.6 mg kg^{-1}) higher than that in the control (17.5 mg kg^{-1}). Application of 2 kg B ha^{-1} to the soil, foliar application (1 or 2 kg B ha^{-1}), and mixed application (1 or 2 kg B ha^{-1} , half in soil and half in leaves) did not provide consistently better productive results.

Soil-applied Ca rate ⁽¹⁾	Soil-applied B rate ⁽²⁾	Leaf-applied B rate ⁽²⁾	Fresh tuberous root yield	Starch yield	B in leaf ⁽³⁾
kg ha ⁻¹			t ha ⁻¹		mg kg ⁻¹
0	0		26.5 no ⁽⁴⁾	7.1 k	12.4 h-k
	1		35.1 a-d	10.9 a	20.5 e
	2		31.4 f-k	8.9 e-i	10.6 kl
		1	27.5 mno	7.9 jk	29.2 a
		2	27.1 mno	8.1 ij	13.3 hij
	0.5	0.5	33.9 b-g	10.0 a-d	21.1 e
	1	1	36.0 ab	10.4 abc	22.7 de
	100	0	29.3 j-n	8.4 g-j	21.2 e
	1		28.1 l-o	7.2 k	13.7 g-j
	2		34.1 a-f	9.7 b-e	14.0 ghi
		1	34.4 a-e	9.7 b-e	18.0 f
		2	33.7 b-g	8.8 e-i	25.3 bc
	0.5	0.5	33.0 c-h	9.3 d-g	14.3 ghi
	1	1	34.5 a-e	9.2 d-h	20.3 f
	200	0	25.8 o	7.0 k	9.3 l
	1		31.6 e-j	9.2 d-h	16.1 fg
	2		31.3 f-k	9.4 def	12.3 h-k
		1	30.0 i-m	9.0 e-i	23.7 cd
		2	28.7 k-n	8.6 f-j	11.6 i-l
	0.5	0.5	29.2 j-n	7.8 jk	15.8 gh
	1	1	32.5 d-i	9.4 def	11.3 jkl
	400	0	29.7 i-m	8.2 hij	17.5 fg
	1		36.8 a	10.1 a-d	21.6 de
	2		32.4 d-i	9.1 d-h	22.0 de
		1	30.7 h-l	8.4 f-j	23.8 cd
		2	30.1 g-k	9.3 d-g	21.0 e
	0.5	0.5	36.0 ab	9.6 cde	21.8 de
	1	1	35.7 abc	10.6 abc	27.1 ab

⁽¹⁾ Calcium applied as limestone before planting.

⁽²⁾ Boron applied as boric acid 2 months after planting.

⁽³⁾ Leaf sampled 4 months after planting.

⁽⁴⁾ Means followed by a common letter within a column are not significantly different by the Duncan's multiple range test ($p < 0.05$).

Source: Adapted from Bowichean et al. [37].

Table 1.

Influence of Ca and B fertilization for cassava on fresh tuberous root and starch yield as well as B concentration in youngest fully leaves in Thailand.

The positive response to B fertilization in this study occurred even at a not very low hot water soluble-B concentration (0.43 mg kg^{-1} at the 0–30 cm soil layer), suggesting that cassava may be more responsive to B supply than previously thought. The responsiveness of cassava to B was also observed in a study carried out in Brazil [38]. However,

the response of the plant was dependent on the cultivar. Application of 1 or 2 kg B ha⁻¹ as boric acid to an Ultisol with a low hot water soluble-B concentration (0.15 mg dm⁻³ at the 0–20 cm soil layer) significantly increased the tuberous root yield of the cultivar BRS 399. Application of 1 kg B ha⁻¹, however, was insufficient to increase the yield of the cultivar IAC 576-70, which required 2 kg B ha⁻¹. The cultivars BRS 399, Palito, and Precoco did not respond positively to B. In the specific case of the cultivar Palito, application of 2 kg B ha⁻¹ reduced the tuberous roots yield, indicating that there was B toxicity with the highest rate of B applied. These findings led the authors to conclude that B application should be cultivar specific.

Although reduced in number, these studies suggest that B fertilization may benefit the production of B-responsive cassava cultivars grown in soils limited in available B.

The concern with B toxicity should be as great as the concern with B deficiency because both nutritional disorders can reduce crop growth and yield. Boron toxicity in cassava is more likely to occur in naturally high B soils or due to accidental application of a high amount of B fertilizer [3, 39]. Symptoms of B toxicity in cassava have been described in the literature. Forno et al. [21] described light-brown necrotic spots in older leaves as initial symptoms in plants grown in solution culture. Subsequently, interveinal areas in these leaves became chlorotic. Finally, a reduction in dry matter yield was observed. The critical B toxicity concentration was suggested to be about 140 mg kg⁻¹ at the top of plants with 40 days of growth. A slightly lower critical concentration (100 mg kg⁻¹) was calculated by Howeler et al. [34] for youngest fully expanded leaf (YFEL) blades of plants grown in solution culture for 9 weeks. The most recent description seems to be that of Silva [3], who observed symptoms in cassava grown for 68 days in pots filled with soil in a greenhouse. This author has described that the symptoms began with a mild chlorosis in the tips and margins of older leaves. The chlorosis increased in size over time. In the sequence, chlorotic tissues became necrotic, and some darker halos appeared on leaf blades. In an advanced stage, tips and margins of older leaves were curved downwards. An old leaf with symptoms is shown in **Figure 1**. Despite the symptoms, there was no significant reduction in plant dry matter. Consequently, it was not possible to calculate the critical B toxicity concentration. However, toxicity thresholds were suggested based on the appearance of visual symptoms. The thresholds in younger leaf blades and older leaf blades were 99.9 and 130.7 mg kg⁻¹, respectively. These thresholds corresponded



Figure 1.
Symptoms of B toxicity in an old leaf of cassava. Photo by Alysson Roberto Baizi e Silva.

to the respective thresholds for hot water soluble B concentration of 0.875 and 0.891 mg dm⁻³. Concentrations above these thresholds in both leaf blades and soil could indicate suspected B toxicity symptoms.

2.2 Copper

The total Cu concentration in the surface layer of tropical soils varies considerably with the parent material. In São Paulo state, Brazil, Valadares [40] found mean concentrations in the A horizon of 189.5 mg kg⁻¹ for soils derived from basic rocks, 27.3 mg kg⁻¹ for soils derived from alluvial and colluvial materials, 22.5 mg kg⁻¹ for soils derived from modern sediments, 8.1 mg kg⁻¹ for soils derived from modern sandy sediments, and 5.2 mg kg⁻¹ for soils derived from sandstone. This study suggests that Cu reserves are high in soils derived from basic rocks and very low in soils derived from sandstone.

The concentration of plant-available soil Cu can be assessed by different extractants. The most common ones are DTPA and Mehlich-1. A comprehensive study conducted in Brazil revealed DTPA-extractable Cu concentrations ranging from 0.1 to 106 mg dm⁻³ for soils from the state of São Paulo and from 0.1 to 56.2 mg dm⁻³ for soils from other Brazilian states, with respective means and medians of 2.5 and 1.4 mg dm⁻³ and 2.3 and 1.3 mg dm⁻³ [18]. The solubility of Cu in soil is mainly controlled by pH and organic matter. Increasing the pH value and organic matter content increases the retention of Cu in the soil [41, 42], decreasing the availability of Cu for uptake by plant roots.

Copper is absorbed as Cu²⁺, but under low Cu availability, Cu²⁺ is reduced to Cu⁺ and subsequently taken up by specific transporters [25]. Copper plays several roles in plant physiology, including involvement in photosynthesis, respiration, defense against oxidative stress, carbohydrate, lipid and nitrogen metabolism, and lignification. It is present in enzymes such as plastocyanin, superoxide dismutase, cytochrome c oxidase, ascorbate oxidase, diamine oxidases, and polyphenol oxidases [25]. For cassava, a study showed that the expression and activity of superoxide dismutase increased with increasing temperature, alleviating the damage caused by heat-induced oxidative stress [43]. Under Cu deficiency, the functioning of this enzyme would be inefficient, and the plant would suffer more with the increased temperature.

Symptoms of Cu deficiency in cassava have been described in the literature. In solution culture, plants exhibited chlorosis and deformation in younger leaves, often with necrosis at the leaf tip, leaf margins cupped upwards, and reduction in number of lobes under severe deficiency [39]. Critical Cu deficiency concentration was calculated to be 6 mg kg⁻¹ in YFEL blades of plants grown in solution culture for 9 weeks [34]. Copper deficiency has not been observed in the field, except in organic soils [34], which retains Cu in forms not absorbable by plants. Under such conditions, cassava can respond positively to Cu fertilization.

Two field experiments conducted in peat soils of Malaysia confirm the productive benefits of Cu application for cassava [44]. In the first experiment, effects of B, Cu, Fe, Mn, Mo, and Zn application were tested. Of all these micronutrients, cassava responded only to Cu. A single application of 20 kg ha⁻¹ of copper sulfate in the first year increased by about 3-fold the tuberous root dry matter yield and starch yield in two consecutive seasons (Table 2). In the second experiment, three application rates of copper sulfate were tested. Application of 10 kg ha⁻¹ of copper sulfate increased tuberous root dry matter yield and starch yield by about 3-fold in the first season and

Copper sulfate (Cu)	Tuberous root dry matter		Starch	
	1973/74	1974/75	1973/74	1974/75
kg ha ⁻¹	t ha ⁻¹		t ha ⁻¹	
0 (0)	4.44	3.98	3.16	2.88
20 (5)	14.72	13.96	9.72	8.42
LSD ⁽¹⁾ (<i>p</i> = 0.05)	3.64	2.42	3.01	2.29
CV ⁽²⁾ (%)	27.6	18.5	27.9	19.6

⁽¹⁾Least significant difference.

⁽²⁾Coefficient of variation.

Source: Adapted from Chew et al. [44].

Table 2.

Effect of a single application of copper sulfate for cassava cv. Black Twig grown in a peat soil on tuberous root dry matter yield and starch yield in two seasons in Malaysia.

about 6-fold in the second season (**Table 3**). There was no additional benefit in applying 20 kg ha⁻¹ of copper sulfate, except for starch yield in the second season. The Cu concentration in the first fully open leaf associated with the increase in productivity provided by the application of 10 kg ha⁻¹ of copper sulfate was around 14 mg kg⁻¹ in both seasons (**Table 3**). Control plants (no Cu application) exhibited Cu deficiency symptoms, described as chlorosis and wrinkling of younger leaves, upturned leaf margins, leaf blade forming a right angle with the petiole, leaf drop, die-back of defoliated shoot, tuberous roots reduced in number and size, and bushy and stunted

Copper sulfate (Cu)	Tuberous root dry matter	Starch	Cu in leaf ⁽³⁾
kg ha ⁻¹	t ha ⁻¹		mg kg ⁻¹
First season			
0 (0)	4.1	2.7	7.3
10 (2.5)	12.2	7.9	14.4
20(5)	13.1	8.5	15.4
LSD ⁽¹⁾ (<i>p</i> = 0.05)	4.9	3.2	6.8
CV ⁽²⁾ (%)	25	5	26.6
Second season			
0 (0)	2.0	1.3	6.5
10 (2.5)	9.4	9.4	13.9
20 (5)	10.2	6.6	14.7
LSD ⁽¹⁾ (<i>p</i> = 0.05)	3.4	2.2	6.6
CV ⁽²⁾ (%)	19	18	25.1

⁽¹⁾Least significant difference.

⁽²⁾Coefficient of variation.

⁽³⁾Leaf sampled 3 months after planting.

Source: Adapted from Chew et al. [44].

Table 3.

Effect of a single application of copper sulfate for cassava cv. Black Twig grown in a peat soil on tuberous root dry matter yield, starch yield, and Cu concentration in the first fully open leaf in two seasons in Malaysia.

plant. The Cu concentrations in the first fully open leaf of the control plants were 7.3 mg kg^{-1} in the first season and 6.5 mg kg^{-1} in the second season (**Table 3**). In conclusion, fertilization with 10 kg ha^{-1} of copper sulfate (or $2.5 \text{ kg Cu ha}^{-1}$) for cassava grown in peat soils of Malaysia was suggested by the authors of this study.

Copper toxicity has not been reported in the literature. However, it may occur in specific situations. One of these situations is the cultivation of cassava in high-Cu soils due to repeated applications of Cu-based pesticides to previous crops [39]. No description of symptoms of Cu toxicity for cassava was found. For plants in general, the symptoms are very generic, consisting of chlorosis and necrosis, stunting, and inhibition of root and shoot growth [45]. Howeler et al. [34] determined a critical Cu toxicity concentration in YFEL blades of plants grown in solution culture for 9 weeks. The value calculated by the authors was 15 mg kg^{-1} . Concentrations above this limit may indicate Cu toxicity in young cassava plants.

2.3 Manganese

The total Mn concentration in tropical soils seems to vary according to soil texture. Catani and Gallo [46] determined total Mn in the surface layer of some soils in the state of São Paulo, Brazil. The highest concentration was found in a clayey soil (2000 mg kg^{-1}) and the lowest in a sandy soil (514 mg kg^{-1}). This difference reflects the Mn concentration in parent material and suggests lower reserve of Mn in coarse-textured soils.

As for Cu, DTPA and Mehlich-1 also are extractants used to evaluate soil Mn available to plants. In the survey carried out in Brazil by Abreu et al. [18], DTPA-extractable Mn concentrations ranged from 0.1 to 325 mg dm^{-3} for soils from the state of São Paulo and from 0.1 to 315 mg dm^{-3} for soils from other Brazilian states, with respective means and medians of 16.1 and 8.8 mg dm^{-3} and 14.9 and 8.3 mg dm^{-3} . Several factors affect Mn availability in soils, such as soil moisture, temperature, depth and pH [47]. Soil pH seems to be the main factor controlling the available Mn concentration, which decreases with increasing pH [48]. The decrease in Mn availability due to reduced soil acidity compromises Mn uptake by plants.

Manganese is absorbed only as Mn^{2+} , and Mn^{2+} can be oxidized to Mn^{3+} and Mn^{4+} within the plant [25]. Manganese plays an important role in photosynthesis, metabolism of proteins, carbohydrates and lipids, cell division and extension, and in the composition or activation of enzymes, many of which are related to the defense system against oxidative stress [25]. These functions are impaired when Mn supply is insufficient, and symptoms of Mn deficiency may appear in plants. The most common symptoms are described as interveinal chlorosis in younger leaves, brown necrotic spots in older leaves, and decreased plant growth and yield [25]. For cassava, critical Mn deficiency concentration of 50 mg kg^{-1} in YFEL blades of plants grown in solution culture for 9 weeks was determined by Howeler et al. [34].

Symptoms of Mn deficiency in cassava have been reported in Brazil. Santos and Tupiramá [49] reported these symptoms in several cassava growing areas in the state of Sergipe, northeastern Brazil. The symptoms include interveinal leaf chlorosis with poor root yield. Interveinal chlorosis was confirmed as a symptom of Mn deficiency in 15 plots of an experiment conducted by the authors in an Ultisol. Such nutritional disorder occurred when Mn concentration in middle leaves was below 20 mg kg^{-1} and soil pH in water above 5.8, as well as at exchangeable Ca and exchangeable Ca + Mg concentrations above 3.8 and $5.2 \text{ cmol}_c \text{ dm}^{-3}$, respectively. These values give an idea of some conditions under which this deficiency may arise. In a cassava crop grown

in a medium-textured soil (Oxisol) in the state of Minas Gerais, southeastern Brazil, interveinal chlorosis in younger leaves associated with Mn deficiency was identified by Malavolta et al. [50]. In this case study, the deficiency concentrations in the leaf blade and petiole were respectively 16 and 24 mg kg⁻¹, at the onset of symptoms, and 12 and 10 mg kg⁻¹, at the most advanced stage of symptoms. Symptoms of Mn deficiency have also been observed in commercial cassava fields in the state of Pará (Figure 2). The occurrence of Mn deficiency opens the possibility of obtaining positive responses to Mn application.

Several Mn fertilization treatments for cassava under organic management in the Federal District, Brazil, were tested in a field experiment conducted by Marchi et al. [51]. Application of 4.28 kg Mn ha⁻¹ as Mn sulfate banded in a clayey Oxisol with a Mehlich-1-extractable Mn concentration of 29 mg dm⁻³ did not result in an increase in tuberous root yield (Table 4). In contrast, Mn applied at stem cutting or spraying Mn on leaves significantly increased root yield (Table 4). Soil application was not



Figure 2.
Symptoms of Mn deficiency in younger leaf of cassava in a commercial field in the municipality of Tracuateua, state of Pará, Brazil. Photos by Alysson Roberto Baizi e Silva.

Mn treatment	Fresh tuberous root yield
	t ha ⁻¹
T1: Control (no Mn)	3.6 b ⁽⁵⁾
T2: 4.28 kg Mn ha ⁻¹ applied to soil ⁽¹⁾	3.9 b
T3: Mn applied to stem ⁽²⁾	16.6 a
T4: T3 + T2	18.1 a
T5: T3 + T2 + S ⁽³⁾	19.5 a
T6: Leaf Mn spraying ⁽⁴⁾	19.4 a

⁽¹⁾ Manganese sulfate banded before planting.

⁽²⁾ Stem cutting immersed in a 5% Mn sulfate solution for 15 minutes.

⁽³⁾ S⁰: elemental sulfur banded before planting.

⁽⁴⁾ Spraying of a 0.5% Mn sulfate solution on leaves.

⁽⁵⁾ Means followed by a common letter within a column are not significantly different by the Tukey's test ($p < 0.05$).

Source: Adapted from Marchi et al. [51].

Table 4.
Effect of different Mn treatments on cassava cv. IAC 576–70 under organic management on fresh tuberous root yield in the Federal District, Brazil.

efficient in this case probably due to the high soil pH in water (6.75), which may have reduced the availability of applied Mn. The mean Mn concentrations in the fourth fully expanded leaf collected 4 months after plant emergence and in leaves collected at harvest (1 year after planting) did not adequately reflect the Mn treatments and were very low ($\leq 12 \text{ mg kg}^{-1}$). Furthermore, plants in all treatments showed interveinal chlorosis and uniform chlorosis in upper and middle leaves as symptoms of Mn deficiency. This study shows how preventing or correcting a Mn deficiency in cassava can be difficult.

Manganese toxicity is not so common in cassava, perhaps because it is a plant tolerant to soil acidity factors, including excess Mn. Symptoms of Mn toxicity in cassava include small dark spots concentrated along the veins on older leaves, followed by yellowing of these leaves [39]. Howeler et al. [34] obtained a critical Mn toxicity concentration in YFEL blades of plants grown in solution culture for 9 weeks. This concentration was calculated to be 250 mg kg^{-1} . Manganese toxicity in young cassava plants would be more likely to occur in concentrations above this value.

2.4 Zinc

The total Zn concentration in the surface layer of tropical soils also varies with the parent material. Valadares [52] analyzed total Zn in 227 samples from 28 soil profiles representative of the state of São Paulo, Brazil. Total Zn concentrations in the A horizon ranged from 87 to 315 mg kg^{-1} for soils derived from basic rocks, from 53 to 84 mg kg^{-1} for soils derived from alluvial and colluvial materials, from 29 to 65 mg kg^{-1} for soils derived from modern sediments, from 16 to 30 mg kg^{-1} for soils derived from sandstone, and from 1 to 17 mg kg^{-1} for soils derived from modern sandy sediments. Thus, Zn reserves tend to be higher in soils derived from basic rocks and lower in soils derived from modern sandy sediments.

Plant-available soil Zn is often assessed by DTPA and Mehlich-1 extractants. In Brazil, a survey showed DTPA-extractable Zn concentrations ranging from 0.1 to 453 mg dm^{-3} for soils from the state of São Paulo and also from 0.1 to 453 mg dm^{-3} for soils from other Brazilian states, with respective means and medians of 4.8 and 1.6 mg dm^{-3} and 4.4 and 1.6 mg dm^{-3} [18]. Soil pH is the most important factor controlling Zn solubility in soils. Numerous studies show that the available Zn concentration decreases with increasing soil pH [53]. When Zn availability decreases, Zn uptake by plant roots is reduced.

Zinc is mainly absorbed by plants as Zn^{2+} [25]. Zinc is a component and activator of many enzymes (e.g., alcohol dehydrogenase, carbonic anhydrase, superoxide dismutase). Therefore, it plays several physiological roles in plants, such as (i) protein synthesis, (ii) carbohydrate metabolism, (iii) tryptophan and indole acetic acid (IAA) synthesis, and (iv) membrane integrity and lipid peroxidation [25]. As a component of superoxide dismutase together with Cu, Zn also plays an important role in reducing damage caused by oxidative stress in plants including cassava, as Lee et al. [43] demonstrated.

Cassava is very susceptible to Zn deficiency [25]. This nutritional disorder has been observed in several parts of the world and can be induced by liming [39]. Typical symptoms of Zn deficiency in cassava include chlorosis in younger leaves, small leaves, narrow leaf lobes, and necrotic leaf tips [39]. Critical Zn deficiency concentration in YFEL blades of plants grown in solution culture for 9 weeks was calculated to be 30 mg kg^{-1} [34]. Concentrations below this value may suggest Zn deficiency. Because of its susceptibility to Zn deficiency, cassava has been considered a plant responsive to Zn application.

Positive responses of cassava to Zn fertilization have been observed under quite different conditions. In Australia, application of 8 kg Zn ha⁻¹ as Zn sulfate broadcasted to a soil replaced after bauxite mining significantly increased fresh tuberous root yield from 5.7 (control) to 16.2 t ha⁻¹ [36]. Also in Australia, a study showed that prior soaking of stem cuttings in Zn sulfate solutions varying from 17.4 to 348 mmol Zn L⁻¹ improved initial growth and increased Zn concentration in leaf blades of cassava grown in pots filled with a lateritic soil [54]. In Brazil, Silva et al. [55] grew cassava in large plastic boxes filled with a low-Zn Oxisol (DTPA-extractable Zn concentration of 0.4 mg dm⁻³) subjected to Zn sulfate rates ranging from 0 to 6 g per plant. Zinc sulfate application increased root dry matter yield up to an estimated rate of 2.5 g per plant. For field application, Zn rates of 5–10 kg ha⁻¹ as banded Zn sulfate at planting or by incorporation of ZnO before planting have been suggested [39].

Zinc toxicity in cassava under field conditions has not been reported in the literature. Howeler et al. [34] determined a critical Zn toxicity concentration in YFEL blades of plants grown in solution culture for 9 weeks. The critical concentration was calculated to be 120 mg kg⁻¹. Zinc concentrations above this value would indicate Zn toxicity.

3. Biofortification

Micronutrient deficiencies affect a large proportion of the world's population [56]. These deficiencies occur mainly in infants, children, and women living in developing countries [56]. Among the most common deficiencies are those of Fe and Zn [57, 58]. The main disorder caused by Fe deficiency is anemia [59]. Other clinical manifestations of Fe deficiency include reduced growth and low immunity [59]. Zinc deficiency also reduces growth, and it can cause serious skin lesions, including the formation of rashes [59].

Cassava root-based diets have been a risk factor for Fe and Zn deficiency in children. A survey conducted in Kenya and Nigeria revealed that rural children aged 2–5 years who consumed cassava as a staple food rich in calories had low intakes of these micronutrients [60]. The intakes of Fe and Zn were below their minimum limits in 78 and 69% of the children surveyed in Kenya and 43 and 59% of the children surveyed in Nigeria, respectively. These high proportions of children subjected to mineral malnutrition were associated with low concentrations of these micronutrients in the tuberous roots of cassava, when expressed per unit of calories (1.6 µg kcal⁻¹ for Fe and 0.2 µg kcal⁻¹ for Zn). In fact, cassava roots have been shown to be very low in Fe (19 mg kg⁻¹) and Zn (10 mg kg⁻¹) [61].

Supplementation, food fortification, and dietary diversification are considered traditional methods of combating mineral malnutrition. However, these methods have not been fully effective due to poor logistics, inconsistent policies, inadequate social infrastructure, and a lack of continued investment [8]. In this context, biofortification emerges as an alternative method to combat malnutrition. Biofortification consists of increasing micronutrient concentrations in the edible parts of food crops through breeding or fertilization [7–9]. Both strategies have been used to biofortify cassava.

Biofortification of cassava with Fe has been based on genetic transformation. Ithemere et al. [62] introduced a gene from an alga into a cassava cultivar. The gene is *FEA1*, and it was taken from the algae *Chlamydomonas reinhardtii*. This gene has the specific function of facilitating Fe uptake. As a result of the introduction of the *FEA1* gene, the transgenic cassava accumulated more Fe in its roots. The Fe concentration

in the tuberous roots of the modified cultivar was 36 mg kg^{-1} , whereas the nontransgenic cultivar had an Fe concentration of only 10 mg kg^{-1} . This genetic modification increased the Fe level in roots by almost four times. This increase was sufficient to meet the minimum daily requirement for Fe in a 500 g meal.

In another example of genetic biofortification, Narayanan et al. [63] overexpressed the gene *AtVIT1* in cassava. *AtVIT1* encodes a vacuolar Fe transporter (VIT1) in *Arabidopsis thaliana*. Under greenhouse conditions, transgenic cassava containing the *AtVIT1* gene had three to four times more Fe in tuberous roots than nontransgenic cassava. Later Narayanan et al. [64] confirmed the efficiency of cassava biofortification with the *AtVIT1* gene under field conditions. The authors found 3–7 times higher concentrations in the tuberous roots of transgenic cassava than in nontransgenic cassava. In the same study [64], the co-expression of two genes was tested. The Fe transporter *IRT1* and ferritin *FER1* genes were taken from *A. thaliana* and introduced into cassava. Under field conditions, the concentrations of Fe and Zn in the tuberous roots of transgenic cassava with *IRT1* + *FER1* were respectively 7–18 and 3–10 times higher than those in the tuberous roots of nontransgenic cassava. These increases could provide 40–50% of the Fe requirement and 60–70% of the Zn requirement of 1- to 6-year-old children.

These results show that biofortification based on genetic engineering is very efficient. Traditional breeding techniques, such as simple selection, can also be used, since there is great genetic variability for Fe and Zn concentrations in cassava [65]. Inacio et al. [66] evaluated 20 cassava genotypes in Nova Andradina, Mato Grosso do Sul state, Brazil. The genotypes MS018, DG014, and DG839 were very productive and presented the highest concentrations of Fe (above 10 mg kg^{-1}) and Zn (above 8 mg kg^{-1}). The authors suggested the inclusion of these three selected genotypes in biofortification programs.

Genetic biofortification relies on plant breeding, which is an expensive and time-consuming process, even with the use of modern genetic engineering techniques. On the other hand, agronomic biofortification, based on soil or plant fertilization, is a simpler alternative to increase the concentration of micronutrients in cassava roots. For Zn, studies have shown interesting results. In Nigeria, Binang et al. [67] found an increase of 79% in Zn concentration in fresh roots and root processing products (89% for *gari* and 79% for *lafun*) by foliar application of 3 kg Zn ha^{-1} as Zn sulfate. Zinc fertilization resulted in Zn concentrations of 18.3, 19.5, and 15.9 mg kg^{-1} for fresh roots, *gari*, and *lafun*, respectively. In the control (no Zn application), fresh roots, *gari*, and *lafun* had lower Zn concentrations (10.2, 10.3, and 8.9 mg kg^{-1} , respectively). In Brazil, Corguinha et al. [10] found clone-specific responses to total Zn concentration in soils. This led the authors to suggest a combination of genetic and agronomic strategies to biofortify cassava with Zn.

4. Research needs

This study shows promising results for micronutrient fertilization in cassava. However, there is a lack of information to guide better this practice. Response curve experiments conducted under field conditions are needed to determine rates of application and critical concentrations of micronutrients in soil and plants. Opportunities exist for experiments with Cu in mineral soils. In northern Brazil, for example, there is an important cassava-producing region whose soils have low concentrations of DTPA-extractable Cu (0.1 mg dm^{-3}) [68]. In this region, a Cu response curve

experiment could produce important results to improve the crop's yield. Organic wastes and other strategic sources of micronutrients for cassava [69, 70] should be evaluated for agronomic efficiency. The role of microorganisms in the acquisition of micronutrients by the plant needs to be further studied. Comparison between soil application and foliar application of micronutrients is crucial to define the most appropriate method to biofortify cassava.

5. Conclusion

The results presented in this chapter have shown that B, Cu, Mn, or Zn fertilization can increase the tuberous root yield of cassava, thus refuting the widespread assumption that the plant is capable of obtaining the required amounts of these micronutrients without fertilizer application. Genetic biofortification based on transgenics is efficient in increasing Fe and Zn concentrations in cassava roots. The increase in Zn concentration can also be achieved by agronomic biofortification, based on the use of fertilizers. Combination of genetic and agronomic strategies to biofortify cassava needs to be studied. In addition, further studies are needed to establish criteria for large-scale application of micronutrient fertilizers in cassava. Use of genetically biofortified cultivars and judicious application of micronutrients are essential to increase production and improve the nutritional quality of cassava and thus ensure food security in the tropics.

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Conflict of interest

The author declares no conflict of interest.

Author details

Alysson Roberto Baizi e Silva
Embrapa Amazônia Oriental, Belém, Brazil

*Address all correspondence to: alysson.silva@embrapa.br

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Chapter 4

Sweet Potato (*Ipomoea batatas* [L.] Lam.) Breeding: From Reproductive Biology to Variety Development

Alfredo Morales, Iván Javier Pastrana Vargas, Dania Rodríguez, Jia ZhaoDong, Peiyong Ma and Bian Xiaofeng

Abstract

The sweet potato is a pivotal crop for global food security due to its adaptability and nutritional value. This chapter explores its genetic improvement, spanning reproductive biology to variety development. It addresses the challenges posed by its complex hexaploid genetics and sporophytic self-incompatibility system, which limits inbreeding and enhances genetic diversity. The chapter details the inheritance patterns of traits such as skin color and root shape, which are influenced by polyploidy and environmental effects. Furthermore, it describes advanced methodologies for directed crosses, flowering induction under artificial conditions, and controlled pollination techniques, essential for overcoming reproductive barriers. The chapter also outlines a structured breeding program comprising seven stages: from hybridization and preliminary selection through genotype-by-environment ($G \times E$) interaction studies to variety release. Emphasis is placed on phenotypic stability, pest resistance, and abiotic stress tolerance. Synthesizing technical and practical knowledge, the chapter offers a comprehensive guide for plant breeders and agricultural scientists dedicated to innovating this vital crop.

Keywords: biofortification, flowering, hybridization, improvement, stability, thermotolerance, varieties

1. Introduction

Sweet potato (*Ipomoea batatas* [L.] Lam.) has solidified its role as a cornerstone of twenty-first-century agriculture, owing to its adaptability to marginal soils and potential to address global challenges such as malnutrition and climate change. Its evolutionary origin, marked by a unique polyploidization event, has conferred exceptional genetic plasticity alongside reproductive complexity that complicates conventional breeding. Distinctively, sweet potato exhibits genomic features of both autopolyploids and allopolyploids, an enigma resolved only recently through advanced molecular tools.

The sporophytic self-incompatibility system, mediated by multifunctional S-alleles, functions as a double-edged sword: while preserving natural diversity, it imposes technical hurdles in targeted hybridization programs. Overcoming this requires innovative approaches, such as grafting onto *Ipomoea carnea* to induce flowering in recalcitrant genotypes. Furthermore, sweet potato's propensity to produce transgressive segregants, valuable for extreme trait combinations, demands robust statistical methods to disentangle genetic potential from environmental noise.

Agriculturally, sweet potato now transcends its subsistence role. Biofortified varieties rich in β -carotene or anthocyanins meet niche market demands, while water-efficient genotypes emerge as solutions for arid regions. This chapter synthesizes decades of research and anticipates future scenarios where multidisciplinary integration will accelerate breeding of varieties that optimize yield, quality, and resilience.

2. Genetics and incompatibility

2.1 Genetics

The sweet potato (*Ipomoea batatas* [L.] Lam.) is a hexaploid species ($2n = 6x = 90$), with a basic number of $x = 15$ [1]. Its genomic constitution, important for population genetics, remains debated, with proposed origins for *I. batatas* including strict autopolyploidization [2] and allopolyploidization [3, 4]. Recent molecular evidence indicates an auto-allopolyploid with some preferential meiotic pairing [5], supporting models of autopolyploid [6] or segmental allopolyploid [7], thereby excluding strict allopolyploidy.

The species' genomic formula is designated as $B_1B_1B_2B_2B_2B_2$, where the B_1B_1 subgenome represents the diploid progenitor and $B_2B_2B_2B_2$ the tetraploid progenitor [8]. Current models propose that the tetraploid progenitor of *I. batatas* was formed *via* allopolyploidization ~800,000 years ago, followed by hybridization with a diploid progenitor and subsequent genome duplication ~500,000 years ago, ultimately yielding cultivated *I. batatas* [9].

2.1.1 Inheritance of characters

Linkage mapping confirms polysomic inheritance in sweet potato [5], with proposed disomic, tetrasomic, tetradisomic, and hexasomic inheritance models [10, 11]. Unlike diploids, which have three genotypes at a biallelic locus (AA, Aa, and aa), autohexaploids exhibit seven possible genotypes (A^6 , A^5a , A^4a^2 , A^3a^3 , A^2a^4 , Aa^5 , and a^6) [12]. In a $6x$ system, within an allele frequency range of approximately $q \approx 0.2$ – 0.8 , the heterozygosity frequency remains >0.75 [13], indicating substantially higher heterozygosity retention.

For leaf shape, there is incomplete dominance of lobed leaves over non-lobed leaves. This trait follows a quantitative inheritance pattern, likely involving multiple genes with additive effects. Regarding tuberous root flesh color, there is incomplete dominance of white and purple over orange. In crosses between white-fleshed and purple-fleshed parents, phenotypic segregation showed a 1:2:1 ratio (white-cream:purple:codominant).

Tuberous root shape is strongly influenced by the environment ($H \sim 30\%$). However, in crosses between parents with root surface defects, only 11.74% of

the progeny had smooth skin, whereas crosses between smooth-skinned parents increased this percentage to 32.42%. This suggests an additive effect of the genes controlling this trait and indicates that only defect-free, smooth-skinned parents should be used (**Figure 1**) [14].

There may be a potential linkage between purple skin and flesh color. In contrast, red and yellow skin colors segregate independently of flesh color. No relationship exists between flesh color and smooth skin presence, indicating these traits are inherited independently [14].

Sweet potato exhibits transgressive segregation for both flesh color and root shape, enabling the development of individuals with extreme characteristics (superior or inferior to parents). This is particularly relevant for breeding programs seeking novel trait combinations.

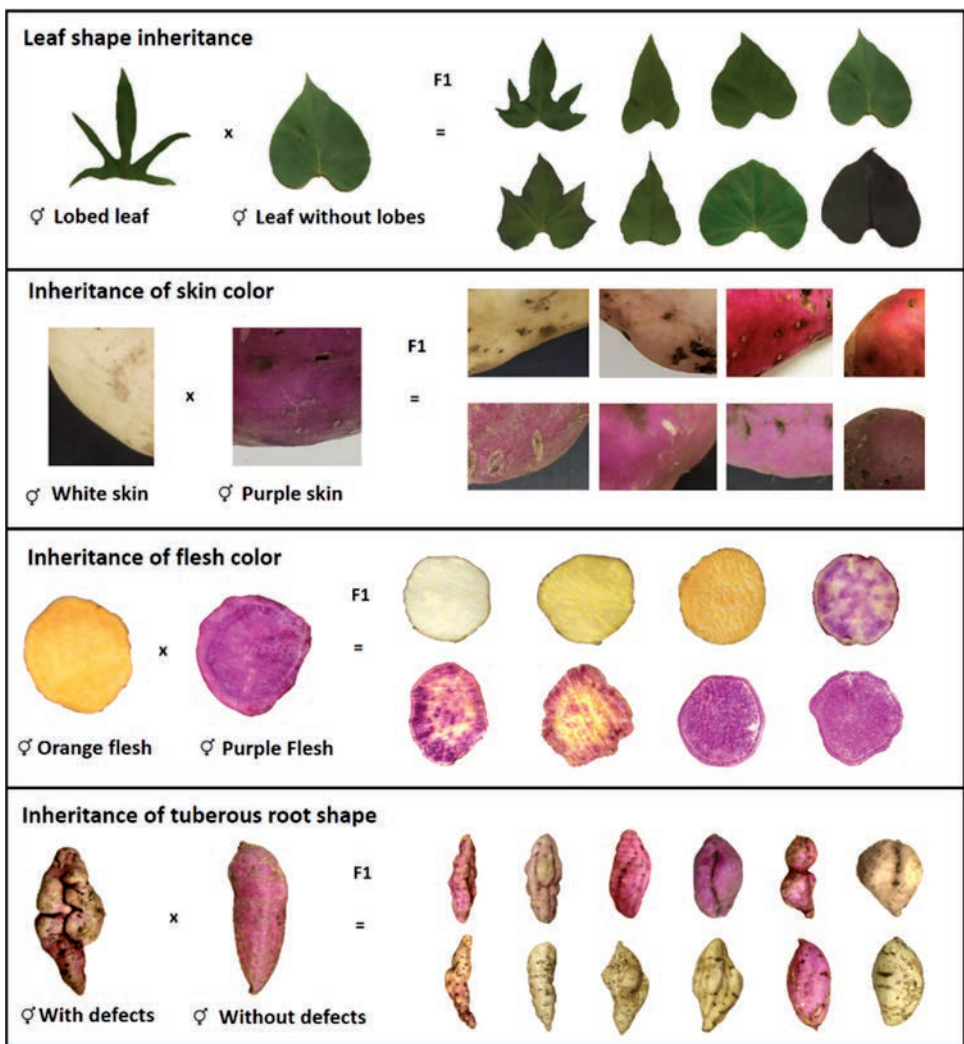


Figure 1.
Graphical representation of the inheritance of traits in sweet potato.

2.2 Self-incompatibility

Self-incompatibility (SI) constitutes a major barrier in sweet potato breeding programs. This system limits parental selection, reduces the genetic base available for generating segregating populations, and hinders both trait fixation and progeny evaluation [15]. While SI promotes heterozygosity by preventing self-fertilization, enhancing genetic diversity in natural populations, it poses significant challenges in agricultural contexts, particularly in polyploid, highly heterozygosity crops like sweet potato [15, 16].

Sweet potato exhibits a homomorphic, sporophytic, multi-allelic SI system, consistent with other Convolvulaceae [17]. Its mechanism involves inhibition of pollen germination on the stigma when matching S-alleles are expressed in both pollen (determined sporophytically) and stigma tissue [18]. Studies in wild *Ipomoea trifida* have identified 49 different S-alleles, suggesting high genetic diversity within this system [19].

Sporophytic SI in sweet potato is influenced by dominance/recessivity relationships among S-alleles, which determine compatibility or incompatibility patterns in specific crosses [20], resulting in three outcomes: (i) reciprocal compatibility (both directions compatible), (ii) reciprocal incompatibility (both directions incompatible), and (iii) unilateral incompatibility (only one direction compatible) [15]. These patterns suggest allelic interactions where dominant alleles suppress recessive counterparts [19].

Molecular insights suggest the S-locus in *Ipomoea* contains highly polymorphic genes expressed in both stigma and pollen. In *I. trifida*, specific stigma proteins (SSPs) associated with particular S-genotypes have been identified, which are regulated during floral development and reach maximum expression at anthesis [21].

Sterility, distinct from SI, further constrains seed production. Manifestations include (i) chromosomal aberrations, (ii) genomic imbalances, and (iii) pollen tube growth failures [22]. Sterility manifests at stages such as pollen germination, pollen tube growth in the style, or formation of nonviable gametes. Unlike SI, where gametes remain viable but incompatible, sterility involves nonviable gamete formation, potentially linked to secondary genome associations in this hexaploid species [1, 15].

While SI and sterility limit conventional techniques like inbreeding for fixing desirable traits, SI simultaneously facilitates broad genetic variation by naturally restricting self-fertilization in hybridization schemes.

3. Reproductive biology

Flowering in sweet potato is generally influenced by latitude and photoperiod. While prolific in tropical regions, flowering is minimal or absent in temperate regions above 35° latitude. Even within the tropics, the intensity of flowering varies widely with the seasons, from scarce to abundant, and varies greatly by genotype. It is generally recognized that a short photoperiod (≤ 10.5 hours of light) and slight humidity promote sweet potato flowering. Most genotypes flower naturally under long night conditions (more than 13.5 hours of darkness) in the tropics (e.g., Caribbean), without requiring grafting for induction [23].

Flowering phenology typically initiates in November in tropical regions and persists for ~5.5 months until April. Notably, while some genotypes flower year-round, others remain completely nonflowering.

3.1 Floral morphological characteristics

Sweet potato flowers grow from the leaf axils in cymose inflorescences, bearing 1–30 flowers per peduncle, depending on the genotype. Floral buds typically develop in first-, second-, and third-order sequences. Individual flowers attach *via* short pedicels (2–15 mm). The calyx comprises five sepals (two outer, three inner) that persist in the floral axis post-anthesis. Corollas exhibit violet margins and intense purple-reddish mesopetalic zones. Flowers are hermaphroditic [23].

The androecium comprises five stamens covered with glandular hairs, partially adnate to the corolla. Filament length varies with stigma position (heterostyly), positioning anthers below, level with, or above the stigma. Anthers (whitish, yellow, or pink) dehisce longitudinally. Pollen grains are spherical and echinate (surface covered by very small glandular hairs).

The gynoecium consists of a bicarpellate and bilocular pistil (1.5–2.7 mm) with a superior ovary. Each locule contains 1–2 ovules and a bicapitate stigma. Yellow basal glands at the base secrete nectar for insect attraction. The average number of pollen grains per anther is 400 [23].

Sweet potato fruits are spherical capsules (5–10 mm diameter) with a terminal tip, glabrous or hirsute, and dehiscent; they turn brown at maturity. Each capsule contains 1 to 4 seeds (2–3 mm long), brown/black, glabrous, angular, slightly flattened on one side, and convex on the other. Under manual pollination, capsules typically produce only two seeds, while open pollination yields capsules with one to three seeds. Larger seeds germinate first, while smaller seeds, representing 50% of the total obtained, germinate later, depending on the genotypes involved (**Figure 2**).

When stored under well-controlled conditions (18°C and 50% relative humidity), seeds can retain viability for over 20 years [23, 24].

3.2 Inflorescence growth

Upon activation of the axillary floral bud, the peduncle elongates to a final length of 5–15 cm over 18–20 days, after which growth stops and flower emergence begins.

Flowers develop at an average rate of 1.5 days per flower per inflorescence, with most inflorescences producing a new flower every 1 to 2 days. Occasionally, two flowers may open simultaneously in 1 day within the same inflorescence.

Floral production duration varies significantly by genotype, persisting for 10–36 days. The number of flowers per inflorescence ranges from 3 to 30, while the total floral output per plant (for genotypes that flower naturally) reaches 200–800 flowers (**Figure 3**).

3.3 Time from pollination to seed maturation

The time from pollination to seed maturation ranges between 20 and 35 days, with genotype-dependent differences. This duration is strongly influenced by the number of flowers per inflorescence: genotypes bearing more flowers per inflorescence require longer maturation periods, while those with fewer flowers mature faster.

Seed capsules reach harvest readiness when the pedicel turns yellow, followed by complete necrosis within 48 hours (**Figure 4**).



Figure 2.
Morphology of the flower and its reproductive parts, capsule, and botanical seed of sweet potato.

3.4 Anthesis and senescence

Anthesis (onset of floral untwisting) occurs between 0440 and 0600 h in darkness, initiating up to 90 minutes before sunrise in most genotypes. Complete untwisting requires 110–150 minutes. Stamen dehiscence begins simultaneously during anthesis, even before floral untwisting is fully completed (**Figure 5**).

Floral buds are highly sensitive to atmospheric temperature. A temperature drop delays bud opening. When dawn temperatures fall below 10°C, the corolla remains only partially expanded by 10:00 h. This occurs because sweet potato ceases growth at 15°C and does not survive below 12°C.

Each flower opens once, typically initiating wilting by midday. Senescence progression depends on temperature, humidity, and solar radiation; under hot/sunny Caribbean conditions, wilting commenced by 1100 h, whereas cooler/overcast days delayed onset until after 1200 h. The process begins with petal depigmentation and inward contraction. Concurrently, the stigma loses its glossiness and begins



Figure 3.
 Growth of sweet potato inflorescence (numbers mean days).



Figure 4.
 Time from pollination to botanical seed collection (numbers mean days).

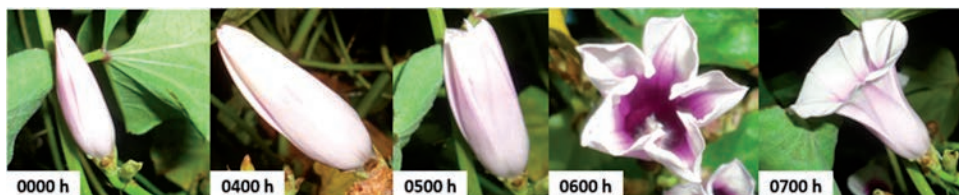


Figure 5.
 Anthesis of the sweet potato flower (the number means time of day).

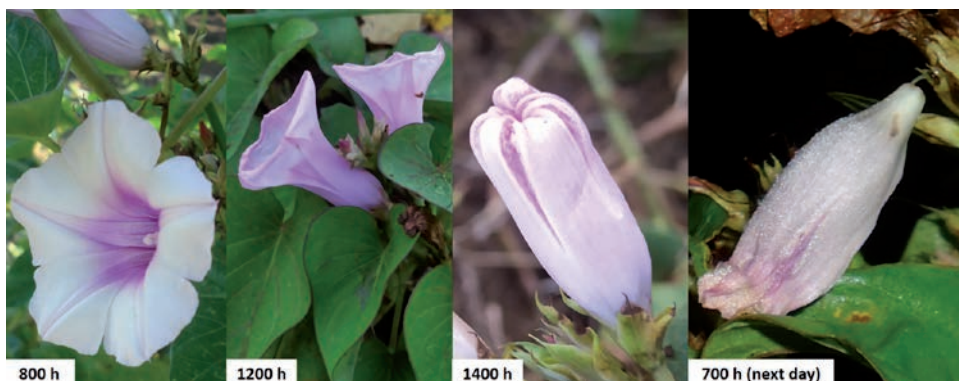


Figure 6.
 Wilting and falling of sweet potato flowers (the number means time of day).

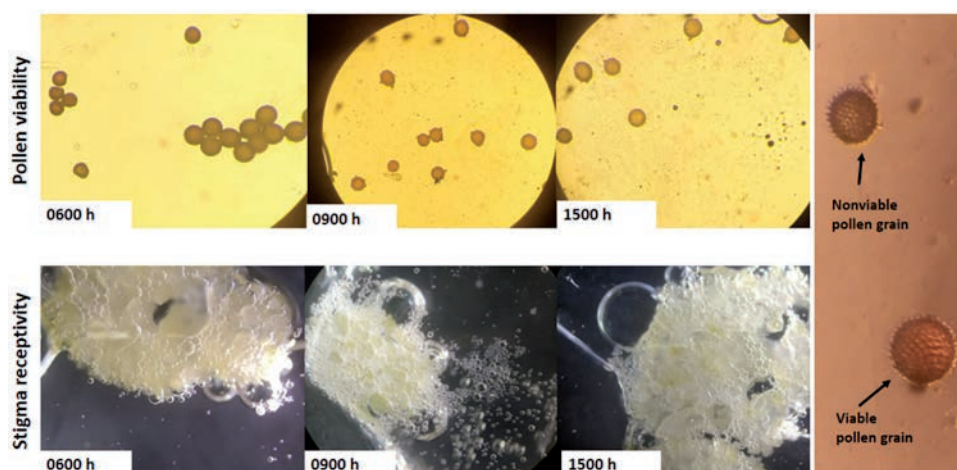


Figure 7.
Pollen viability and stigma receptivity in sweet potato (number means time of day).

to desiccate, later turning brown. Ultimately, the corolla detaches from the pedicel 15–20 hours post-wilting (early next morning), with timing varying by genotype and environmental factors (Figure 6).

3.5 Stigma receptivity and pollen viability

Pollen viability remains high (>90%) from 0600 to 1300 h, declining to ~80% between 1300 and 1500 h. Stigma receptivity is absent prior to anthesis but initiates post-flower opening, ranging from 79 to 93% between 0600 and 0800 h. It peaks at 100% between 0900 and 1100 h before decreasing to ~60% after 1200 h (Figure 7).

4. Stages of a sweet potato breeding program

Sweet potato breeding programs serve as a fundamental strategy for crop improvement, targeting superior genotypes with trait-specific objectives across diverse end-uses, including:

- Human consumption (improved nutritional quality and culinary characteristics).
- Industrial processing (high starch content varieties for value-added products).
- Animal feed (high-yielding forage genotypes).
- Pest resistance (e.g., tolerance to *Cylas formicarius*, the sweet potato weevil).
- Disease resilience (resistance to viral and fungal pathogens).
- Bioactive compounds (enhanced β -carotene or anthocyanin content for nutritional or functional food applications).

Beyond these specific objectives, all improved varieties must meet essential agronomic and quality standards to ensure commercial viability and farmer adoption. These universal requirements include:

- High yield potential (ensuring economic competitiveness).
- Early maturity (reducing field exposure to biotic/abiotic stresses).
- Stability and adaptability (consistent performance across environments).
- Vigor and establishment capacity (high survival rates under field conditions).
- Abiotic stress resilience (drought and heat tolerance for climate adaptation).
- Smooth tuberous root skin (improving postharvest quality and marketability).
- Root uniformity (mechanical harvesting compatibility).
- Adequate dry matter content (>27% for optimal culinary and processing properties).

This dual-focused approach—combining targeted traits with foundational agronomic excellence—ensures new cultivars address niche markets while overcoming broad production challenges, advancing global food security through climate-resilient sweet potato systems.

4.1 Stage I: Crossings and botanical seed harvest

4.1.1 Directed crossing blocks

In the Caribbean region, crossing blocks are established in early September to synchronize with the natural flowering onset in November, when plants reach approximately 60 days of age. Parental genotypes must have known compatibilities to ensure successful hybridization (**Figure 8**).



Figure 8.
Sweet potato crossing block design.

Planting protocol:

- Twelve cuttings per parent were planted at 1 × 1 m spacing with supporting stakes.
- Each parent was allocated to three mounds (four cuttings and four stakes per mound).
- Depending on labor availability, this method typically yields 3000 to 15,000 hybrid botanical seeds.
- The resulting families will consist of full siblings.

Constant humidity must be maintained, as a sudden reduction negatively impacts flower production.

To avoid insect-mediated pollen flow and eliminate the need for daily floral bud covering, crossing blocks should be established in a fully enclosed area protected by anti-aphid mesh or similar barrier netting.

4.1.2 Polycrossing

For breeding programs, 20–30 elite parents are selected based on specific breeding objectives, prioritizing phenotypic superiority and sufficient genetic distance to minimize inbreeding depression and compatibility issues in progeny. A key selection criterion is the prior evaluation of their general combining ability (GCA) and specific combining ability (SCA).

The implemented experimental scheme consists of a Latin square design ($n \times n$), where each parent is evenly replicated across rows and columns. Each experimental plot includes:

- 2 furrows, each 2 meters long.
- Planting spacing: 1.0 m between furrows × 0.25 m between plants.
- Density: 18 plants per parent/plot.

This design offers logistical and economic advantages over traditional crossing blocks, enabling the production of 30,000–100,000 botanical seeds per hybridization cycle. The system's efficiency lies in maximizing genetic recombination, generating of broad genetic variability, and critical success factors.

The success of the breeding program is fundamentally determined by three key factors:

- Capacity to screen large hybrid populations.
- Alignment of selection environments with target production conditions.
- Sufficient genetic variability (even when resulting in half-sib families, **Figure 9**).

Regular monitoring of capsules is essential, as pest insects such as *Euscepes postfasciatus* (Fairmaire) (Coleoptera: Curculionidae) can damage botanical seeds.



Figure 9.
 Spatial design for open pollination.



Figure 10.
 Damage to botanical seeds of sweet potato by *Euscepes postfasciatus*.

The use of biological pesticides is recommended to protect bees and other pollinating insects (**Figure 10**).

4.1.3 Flowering induction

In regions where sweet potatoes do not flower naturally or exhibit poor flowering, the following protocol is recommended:

1. First, rootstock cuttings should be planted in pots. The species *Ipomoea carnea* subsp. *fistulosa* (Martius ex Choisy) D.F. Austin is recommended as rootstock, as it demonstrates superior grafting effects compared to *I. nil* or *I. setosa*. After 30 days, graft sweet potato scions onto rootstock branches (30–60 cm in length).
2. Following completion of all grafts, plants are maintained until grafted sweet potato plants reach approximately 25–30 cm in height. All pots, separated by parent plants, are then placed on transport carts for photoperiod management to induce flowering.

Photoperiod control protocol:

- Daily storage in complete darkness from 4:00 pm until 8:00 am the following day (16 hours of darkness).
- Daily sunlight exposure from 800 to 1600 h (8 hours of light).
- This 16:8 hour dark:light cycle ensures reliable induction of profuse flowering.

Floral buds typically appear 20–50 days after photoperiod initiation (timing varies by genotype). Once flowering begins, directed crossing procedures can commence (**Figure 11**).

4.1.4 Pollination

For precise genetic studies of trait inheritance, flowers designated as female parents must be emasculated the afternoon before pollination (around 1600 h, approximately 14 hours before anthesis). This requires accurate identification of the floral bud's phenological stage (**Figure 12**).

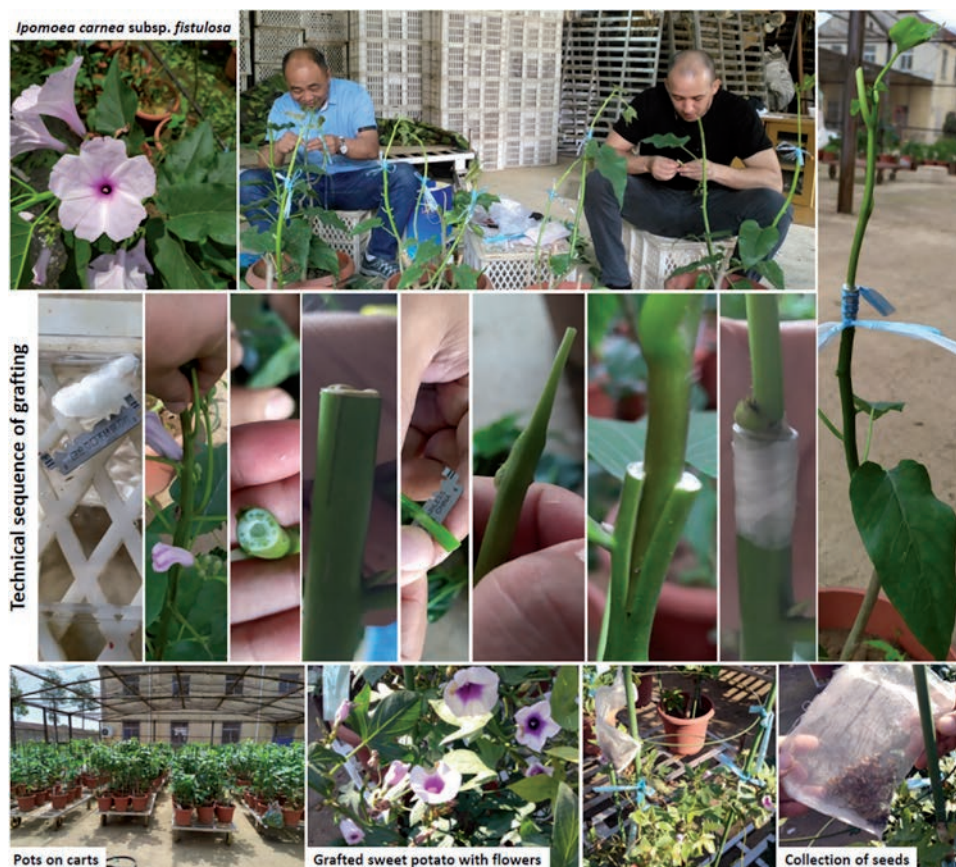


Figure 11.
Grafting process and flowering induction in sweet potato.

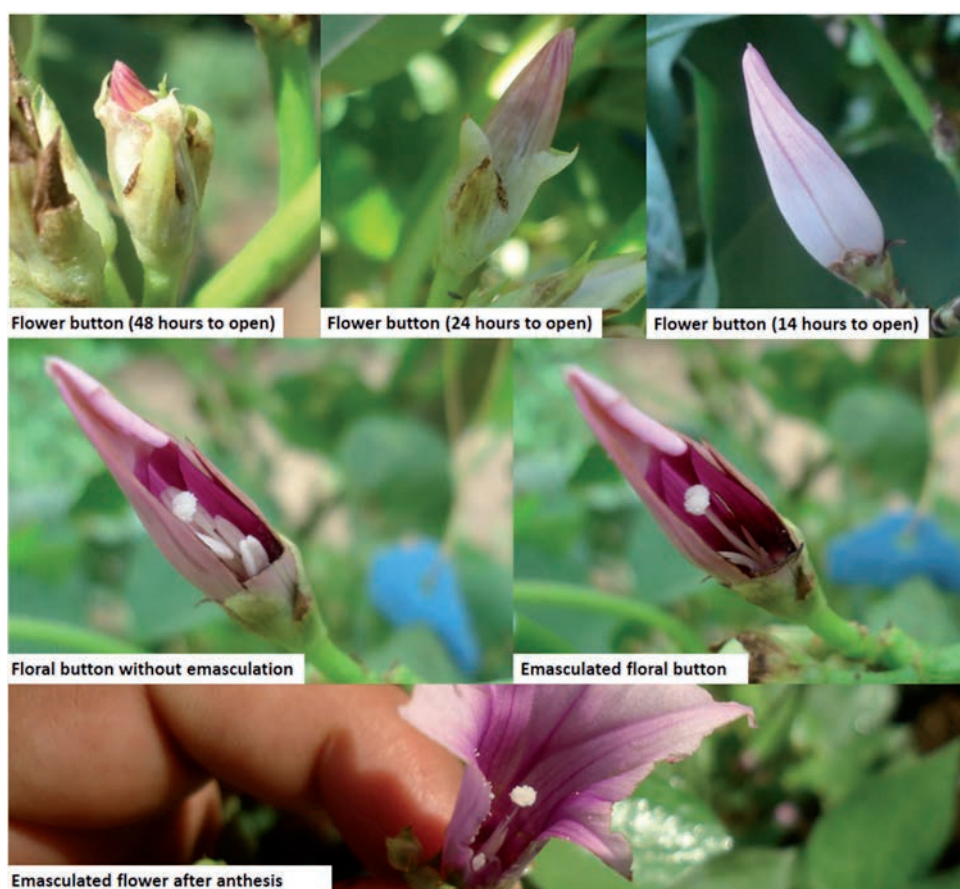


Figure 12.
Phenological stage of floral buds prior to anthesis and emasculation.

In conventional breeding programs, emasculation is unnecessary due to the species' homomorphic sporophytic multiallelic system; natural self-pollination (in self-compatible genotypes) occurs only rarely. For controlled crosses:

- Both female flowers and pollen source flowers (left intact) are covered the preceding afternoon with 3 cm long sections of large straws (0.7 cm diameter).
- Cross-pollinations are conducted the next morning between 0700 and 1000 h.
- Each pollinated flower is labeled with parent information and date, then re-covered with straw sleeves to prevent insect-mediated pollen contamination.
- Daily records of all crosses are maintained (**Figure 13**).

Seed handling protocol:

- Botanical seeds are harvested when flower pedicels show necrosis and are sorted by parentage.



Figure 13.
Manual pollination technique and botanical seed harvest.

- Seeds are cleaned and stored in paper envelopes.
- Each cross receives a family code (e.g., ISS 250#: INIVIT + Seed + Sweet potato +2025 year + family number).

Key observations:

- Success rates: 45–75% of pollinations take place (never 100%), influenced by:
 - Environmental conditions during crossing.
 - Gametic fertility.
 - Seed yield: 1–3 seeds/capsule (typically 2).
- Critical timing: Capsules must be harvested promptly as they dehisce (split open) when overripe, risking seed loss.

4.2 Stage II: Seedling establishment

Sweet potato botanical seeds exhibit slow and irregular germination due to hard seed coats. Pretreatment is essential, and the most common involves chemical scarification by soaking seeds in concentrated sulfuric acid (H_2SO_4 , 98%) in a beaker for 15 minutes. However, this method typically yields only 50–60% germination rates.

The most effective protocol, achieving >90% germination, is manual scarification using nail clippers:

- Make a small incision in each seed coat (**Figure 14**).
- Place seeds in Petri dishes with 2 mm water depth (pre-germination) the day before sowing.
- Maintain underhydration until sowing (24 hours).

Two primary approaches are used as sowing methods for hybrid seeds:

1. Direct nursery sowing (**Figure 15**).

- Spacing: 5 cm between seedlings × 20 cm between rows.
- Advantages: Reduced transplant shock; lower labor cost.

2. Seedling trays (plug cells) (**Figure 15**).

- Transplanting: Move to vegetable chambers 15 days post-sowing.
- Final spacing: 10 cm between seedlings × 20 cm between rows.
- Advantages: Uniform seedling development; easier early-stage management.
- Growth protocol. Regardless of method:
- Seedlings are cultivated for ~50 days post-sowing before field transfer.
- Maintain consistent moisture (avoid waterlogging).
- Provide >12 h daylight for vigorous growth.

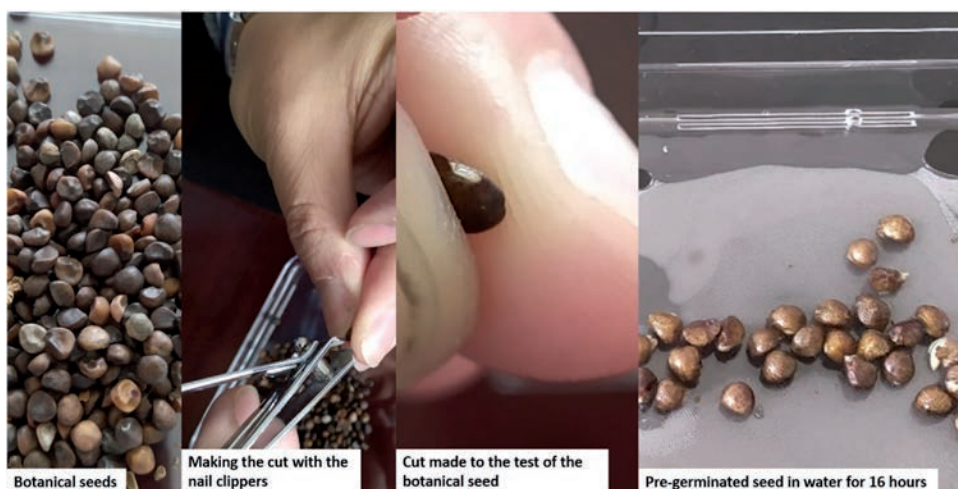


Figure 14.
Manual scarification of botanical seeds.



Figure 15.
Direct sowing vs. plug-tray propagation of botanical seeds.

4.3 Stage III: Field evaluation and preliminary selection

In Caribbean growing systems, F_1 seedlings must be transplanted in May–June to leverage the region’s unique climatic selective pressure. This timing is critical because the subsequent tuberization phase (July–August) coincides with peak nighttime temperatures (26–30°C). These conditions create a powerful phenotypic filter through three physiological mechanisms:

- Elevated root respiration rates that disproportionately consume carbohydrate reserves.
- Disrupted photoassimilate partitioning favors excessive vine growth over storage root development.
- Inhibition of tuberization enzymes (e.g., sucrose synthase).

This environmental stress test efficiently eliminates approximately 50% of genotypes lacking thermotolerance, with surviving individuals demonstrating superior heat adaptation traits.

Planting material preparation:

- Collect 30 cm apical stem cuttings from each F_1 seedling.
- Planting: 0.90 × 0.50 m spacing.

At 120 days after planting (DAP), researchers conduct a comprehensive evaluation:

1. *Storage root morphology*. Immediate discard criteria:

- Longitudinal fissures
- Horizontal constrictions

Rationale: These defects show high heritability.

2. Yield component analysis

- Minimum threshold: ≥ 3 commercial-sized roots/plant (≥ 100 g each). Genetic basis: additive genetic variance, correlation with final yield: $r = 0.79^{**}$ ($p < 0.01$).

3. Pest resistance screening. Focus organism: Sweet potato weevil (*Cylas formicarius*). Resistance mechanisms evaluated:

- Antixenosis (non-preference) and antibiosis (toxic/nutritional).
- Elimination threshold: $\geq 20\%$ root damage (**Figure 16**).



Figure 16.
Genotype selection in the first stage, taking into account independent criteria.

This comprehensive selection protocol ensures that only genotypes with superior genetic potential advance to subsequent evaluation stages, creating a deliberate genetic bottleneck that significantly improves breeding program efficiency. Through this multi-trait approach that balances immediate selection pressure with long-term genetic gain objectives, typically only 10–15% of the original population survives this preliminary evaluation phase.

Since selection at this stage is based on individual plants (unreplicated evaluations), the storage roots of chosen genotypes are carefully preserved. Each selected root is

- Placed in labeled bags marked with the corresponding family code.
- Stored under controlled conditions to prevent dehydration or fungal infection.

The selected roots are planted to generate new propagation material through the following protocol:

- Spacing: 50 cm between plants.
- Planting depth: Covered with 2–3 cm of soil to promote sprouting.
- Irrigation: Immediate watering to stimulate bud activation.
- Growth duration: Maintained for 50 days to develop robust vines for cuttings (**Figure 17**).

Purpose of this phase.

Clonal propagation ensures genetic uniformity in subsequent trials.

Vigorous vine growth provides optimal material for stem cuttings.

4.4 Stage IV: Intermediate stage

Once the time required to obtain new planting material has elapsed, 20 cuttings per genotype are taken and planted in a single-row plot (without replicates), with one row per genotype (20 plants/row). Selection at this stage will be based on the following criteria:



Figure 17.
Planting of the selected genotypes to obtain the new planting material.

- Yield
- Pest tolerance
- Early maturation
- Survival rate at harvest
- Uniformity of tuberous roots

Genotypes may be eliminated using simultaneous selection analysis across multiple traits with independent criteria (**Figure 18**).

On harvest day, the foliage from each plot will be carefully removed by genotype without destroying it. From the selected genotypes, 100 apical cuttings (tip sections only) will be taken and planted in a six-row plot (without replicates), with 20 cuttings per row. Evaluation will occur 120 days later, focusing only on the two central rows. The remaining four rows will not be harvested; their purpose is to provide new planting material for the selected genotypes in the next stage. From the chosen genotypes, 400 cuttings will be collected. The same selection criteria will apply (**Figure 19**).



Figure 18.
Intermediate-stage evaluation.



Figure 19.
Second evaluation in the intermediate stage.

4.5 Stage V: Advanced stage

In this stage, genotype replication begins. Using 400 cuttings per genotype, plots of 100 cuttings each will be planted in five-row arrangements (25 cuttings/row). A completely randomized block design will be employed.

In the Caribbean region, this stage will last 1 year due to the two well-defined growing seasons (spring and winter). Evaluations must be conducted in both seasons, as less stable genotypes often show highly variable responses across seasons. The first elimination will be based on phenotypic yield stability, and one or two control varieties will be included for comparison.

For studying phenotypic stability, the GGE biplot model (**Figure 20**) is recommended due to its unique capabilities:

- Decomposes genotype-by-environment interaction ($G \times E$) into interpretable components (genotype effect + $G \times E$), filtering out noise from the main environmental effect.
- Visualizes complex patterns through intuitive graphs, identifying stable genotypes and mega-environments.
- Unlike other methods (e.g., AMMI models or regression analysis), the GGE biplot enables direct comparison of yield and genotype stability within the same two-dimensional space, streamlining the selection of:
 - High-yielding cultivars.
 - Genotypes with high stability.
 - Adaptable varieties.

From the selected genotypes, all tuberous roots will be harvested to establish an agamic seed bank, which will supply planting material for the next stage (**Figure 21**).

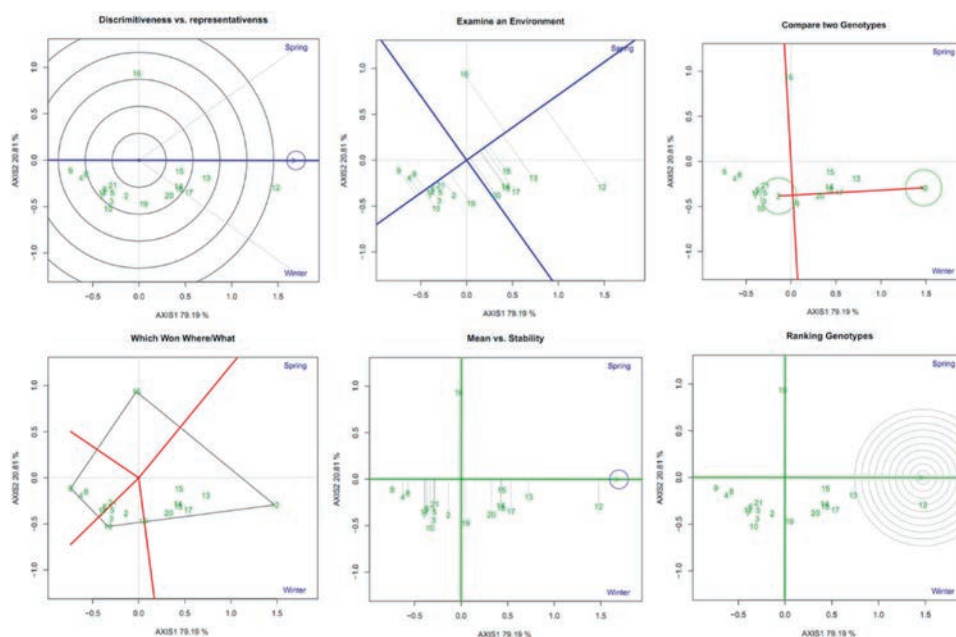


Figure 20.
 GGE biplot model for phenotypic stability analysis.



Figure 21.
 Agamic seed production system for selected genotypes.

4.5.1 Culinary quality and dry matter content evaluation

Additionally, at this stage, the culinary quality and dry matter content of selected materials are evaluated to determine consumer preferences (sweetness, texture, aroma) according to local standards.

Culinary quality assessment methodology:

- Sample: 10 roots per genotype (harvested at physiological maturity).
- Preparation: Uniform cooking (boiling/baking, following regional customs).
- Sensory panel:

- 10–15 male and female evaluators (farmers and consumers).
- 5-point scale evaluation of sweetness, fiber content, moistness, and aftertaste.
- Selection criteria:
 - Minimum score of ≥ 4 in ≥ 3 attributes.
 - Genotypes scoring < 4 are rejected for human consumption regardless of yield performance.

Dry matter content methodology:

- Sample: 3 roots per genotype/environment (central transverse cut)
- Drying protocol:
 - Oven-drying at 80°C until constant weight (72 hours)
 - Calculation: $(\text{Dry weight} / \text{Fresh weight}) \times 100$
- Selection thresholds:
 - Fresh consumption: 25–0%.
 - Processing (e.g., flour production): $\geq 30\%$.

4.6 Stage VI: G × E interaction studies

A critical challenge in sweet potato breeding is the frequent decoupling of high yield potential and stability/adaptability traits [25]. To properly evaluate these characteristics, robust G × E interaction studies (**Figure 22**) must be implemented under carefully designed experimental conditions:

1. Environment selection protocol. A minimum of six contrasting environments is required for evaluation:
 - Four controlled environments simulating standard commercial production conditions.
 - Two stress environments featuring:
 - Low-input agricultural practices.
 - Induced drought stress (a primary limiting factor in tropical cultivation).
2. Field trial specifications:

Final candidate pool: Typically reduced to 5–6 elite genotypes at this stage
Trial locations:

- On-farm testing with experienced growers (participatory selection).
- Commercial sweet potato production fields (real-world validation).

Experimental design requirements:

- Minimum plot size: 4 rows $\times$ 20 plants/row
- ≥ 3 replications per environment (ensuring statistical reliability)

3. Phenotypic stability analysis:

The GGE biplot methodology is strongly recommended due to its:

- Superior variance partitioning (genotype effect vs. $G \times E$ interaction)
- Visual representation of:
 - Genotypic stability patterns
 - Mega-environment identification
 - Ideal genotype selection



Figure 22.
 Differential genotypic responses under uniform environmental conditions (demonstrating $G \times E$ interaction effects).

- Mandatory inclusion of 1–2 control varieties as benchmarks

The two-stress-environment requirement specifically addresses:

- The crop's sensitivity to water availability.
- Need for drought-resilient cultivars in climate change scenarios.
- Economic realities of low-input farming systems.

4.7 Stage VII: Variety multiplication and release

Superior genotype(s) identified through prior evaluations will be formally registered in each country's official plant variety registry. This crucial step ensures legal recognition and intellectual property protection for the new cultivar. Following registration, large-scale propagation employs two complementary methods:

1. Replication of the late-stage multiplication protocol to maintain genetic purity (**Figure 23**).



Figure 23. Variety multiplication workflow, showing the progression from initial propagation material (tuberous roots and cuttings) to certified planting material.



Figure 24.
 Commercial varieties were developed through the breeding program (the figure exclusively shows some successfully released commercial varieties).

2. Field-scale production using cuttings as the primary propagation material, allowing for rapid expansion for commercial distribution (**Figure 23**).

The multiplication process incorporates rigorous quality control measures, including certification by national agricultural authorities and phytosanitary monitoring to guarantee disease-free planting stock. Breeder seed lots will be preserved to maintain the original genetic integrity of the released variety. This stage represents the culmination of the breeding pipeline, transitioning from experimental genotypes to officially recognized, commercially available cultivars adapted to target production environments (**Figure 24**).

5. Conclusion

Sweet potato breeding represents a unique scientific challenge due to its complex reproductive biology and hexaploid genomic structure. This chapter has explored the genetic foundations, incompatibility mechanisms, and advanced hybridization and selection methodologies, providing a comprehensive framework for developing superior varieties. Key findings include the autopolyploid nature of sweet potato, which influences traits such as flesh color and root shape through incomplete dominance and significant environmental effects. The sporophytic self-incompatibility system, while preserving genetic diversity in natural populations, poses technical barriers for targeted hybridization, necessitating strategies like grafting onto *Ipomoea carnea* to induce flowering. Success in controlled pollination protocols and photoperiod-induced flowering has overcome reproductive limitations in recalcitrant genotypes. Additionally, the structured seven-stage breeding program, ranging from early thermotolerance-based selection to genotype-by-environment ($G \times E$) interaction studies, ensures the phenotypic stability and adaptability of new varieties.

Looking ahead, the future of sweet potato breeding lies in integrating emerging technologies with traditional approaches. Gene editing tools like CRISPR/Cas9 could modulate incompatibility alleles (S-locus) or accelerate the fixation of desirable traits, such as high β -carotene content or abiotic stress resistance, addressing long-standing

challenges posed by polyploidy and heterozygosity. Marker-assisted selection, leveraging identified QTLs linked to yield, nutritional quality, and pest resistance (e.g., *Cylas formicarius*), would enable more precise early-stage selection. Predictive modeling and phenomics, powered by artificial intelligence, could further optimize the identification of stable varieties across diverse environments. Equally important is strengthening participatory approaches by involving farmers in the evaluation of candidate varieties to ensure adoption and relevance.

The global impact of these advancements extends beyond scientific knowledge, offering practical solutions to pressing challenges. Biofortified varieties, rich in vitamin A or anthocyanins, can combat malnutrition in vulnerable populations. Water-efficient and heat-tolerant genotypes are critical for sustainable agriculture in arid regions.

In conclusion, sweet potato breeding is entering an era of accelerated innovation, where the synergy of genomics, traditional techniques, and community engagement will be pivotal. This chapter serves as both a guide and an inspiration for researchers, breeders, and policymakers, highlighting the potential of sweet potato as a cornerstone of resilient and nutritious agriculture in the twenty-first century. By translating intricate biology into tangible solutions, the scientific community can unlock the full potential of this remarkable crop to address food security and climate challenges worldwide.

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It is an honor to acknowledge the pioneers of the Cuba-China scientific collaboration in sweet potato breeding, whose intellectual contributions transformed this field:

To Prof. Alfredo Morales Tejón (INIVIT, Cuba), whose scientific brilliance and strategic vision laid the foundation for this alliance. His ability to integrate complex knowledge and foster international cooperation continues to inspire generations.

To Prof. Guo XiaoDing and Prof. Xie YiZhi (JAAS, China), outstanding scientists whose innovative methodologies and rigorous approaches revolutionized our



Figure 25.
Tripartite working meeting between researchers from INIVIT (Cuba) and JAAS (China), (2010).

breeding programs. Their technical contributions have been decisive for the success of this fruitful international collaboration.

For 25 years of uninterrupted partnership (2000–present), this team has demonstrated how academic excellence transcends borders. The jointly developed cultivars, products of their collective ingenuity, now benefit farmers in both hemispheres.

To these extraordinary scientists, whose intellectual contributions redefined sweet potato breeding, we dedicate this work as a testament to their enduring legacy (**Figure 25**).

Finally, to the global sweet potato research community: may this book chapter inspire new collaborations to unleash the full potential of this extraordinary crop in our collective quest for food security.

Conflict of interest

The authors declare no conflict of interest.

Author details

Alfredo Morales^{1*}, Iván Javier Pastrana Vargas^{2*}, Dania Rodríguez¹, Jia ZhaoDong³, Peiyong Ma³ and Bian Xiaofeng³

1 Research Institute of Tropical Roots and Tuber Crops (INIVIT), Villa Clara, Cuba

2 Department of Agronomic Engineering and Rural Development, Faculty of Agricultural Sciences, Universidad de Córdoba, Montería, Colombia

3 Institute of Food Crops, Jiangsu Academy of Agricultural Sciences (JAAS), Nanjing, China

*Address all correspondence to: alfremr88@gmail.com;
ivanpastranav@correo.unicdoba.edu.co

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As essential agricultural staples, cassava, sweet potato, and yams offer unique, robust advantages that are crucial for strengthening local livelihood security and fostering viable industrial growth worldwide. This book provides a focused yet broad-ranging look at these key root vegetables, devoting individual discussions to each. It begins by examining their vital nutritional value and then transitions into the essential strategies for advancing breeding to ensure higher yields and resilience. Following this, the book explores techniques for optimizing production. It concludes with the critical steps needed to preserve their genetic resources, ultimately offering a holistic view of the ongoing development and significance of these three foundational crops.

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