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A Review on Underutilized Crops as Sources of Bioactive Compounds for Nutriceutical Product Development and Sustainable Food Systems

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Abstract: Many neglected and underutilized crops species have been incorporated locally in human diets since time immemorial, especially in sub-Saharan Africa and many Asian countries where they greatly contribute to food and nutrition security but have been globally underexploited. Underutilized crops such as amaranth, moringa, orange – fleshed sweet potato, snake tomato and spider plant represent a promising frontier for nutraceutical product development due to their rich nutrient and bioactive profiles. These crops hold significant potential to address nutritional deficiencies, diversify food systems, and enhance global food security. Their high concentration of micronutrients, antioxidants, and health – promoting phytochemicals underscore their value beyond conventional staples. Advances in processing technology – including controlled drying, fermentation, extrusion, and strategic fortification – are critical to transforming these crops into stable, safe, and consumer – ready products. Innovations in product development have yielded functional noodles, nutrient – dense snacks, value – added beverages, and ingredient powders that leverage the intrinsic nutraceutical qualities of the raw materials. However, processing often leads to degradation of sensitive bioactives, necessitating targeted strategies such as optimized temperature protocols, encapsulation, and minimal processing to enhance bioactive retention. Economic and sustainability considerations further strengthen the case for valorizing underutilized crops; by integrating local smallholder producers into value chains, reducing post – harvest losses, and creating novel market opportunities, these crops contribute to resilient food systems and equitable rural development. Consumer acceptance studies are essential to gauge sensory preferences, cultural relevance, and market readiness, ensuring product success and widespread adoption. Future prospects include integration into precision nutrition frameworks and expanded nutraceutical product pipelines. Overall, underutilized crops thus offer a viable and innovative pathwway for developing sustainable, health – oriented food products.

***Keywords**: Bioactive Compounds; Food Processing Technologies; Food Security; Functional Food Products; Nutraceutical Potential; Value Addition; Underutilized Crops.*

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I. INTRODUCTION

The global food systems continue to face increasing challenges from malnutrition, climate change, and reliance on a few or a narrow range of staple crops. Reference [24, 18] reported that while efforts were made to produce enough food for the increasing population, which resulted in increased demands for food, nutritional quality was inadvertently sacrificed, resulting in widespread micronutrient deficiencies. Global Reports on Food Crises reveals that about 193 million people are currently living in severe food insecurity [80]. In 2020, 720 million to 811 million people experienced hunger, and around 660 million people are likely to face hunger by 2030 [19]. The prevalence of undernourishment increased from 8.4% in 2019 to 9.9% in 2020. Almost 1 in 3 individuals did not have access to adequate food in 2020 [19]. Moderate or severe food uncertainty has been increasing slowly for 6 years and now affects more than 30% of the world's population [19]. Local crop diversity, culture, knowledge, and traditions have been neglected for decades due to policies that have primarily promoted and supported a few major crops [54, 55]. Consequently, in many parts of the world, diets deficient in essential micronutrients and vitamins persist [32, 76].

Roughly 120 million of the millions of known plant species around the world are cultivated as a source of food, out of which nine species supply over 75% of the global plant-derived energy. Major crops such as maize, rice, and wheat dominate global agriculture, yet they provide limited micronutrient and bioactive diversity. In contrast, underutilized or "neglected" crops, which continue to be overlooked in mainstream agriculture and are largely confined to traditional or regional use, with minimal institutional support [30], offer rich reservoirs of vitamins, minerals, and bioactive compounds with potential health benefits [56]. Their valorization into nutraceuticals and functional food products represents a dual opportunity: enhancing dietary diversity while contributing to sustainable food systems. Despite their promise, these crops remain neglected due to limited research, processing technologies, and weak commercialization frameworks [15].

This review explores the selected underutilized crops: amaranth, moringa, spider plant, orange-fleshed sweet potato (OFSP), and snake tomato. It highlights their rich nutritional and phytochemical profiles, processing technologies, bioactive retention and stability, as well as discusses the development of food-based products from these crops, exploring the challenges, opportunities, and future directions in commercializing these crops. This review is a valuable resource for policymakers and research professionals, providing insights that can inform policy decisions and guide future research. It emphasizes the potential of these crops to contribute to sustainable agriculture and global food security, encouraging investment in their development.

II. NUTRITIONAL AND PHYTOCHEMICAL PROFILES OF UNDERUTILIZED CROPS

A major health issue that directly affects approximately two billion people worldwide is micronutrient deficiency, otherwise known as 'hidden hunger' [31, 84]. Inadequate supply of essential vitamins and minerals impairs the proper growth and development of the body [31, 5, 6]. Iron (Fe) deficiency is a widespread micronutrient disorder in developing countries, where a large number of women and children are affected annually. Moreover, it is the only nutrient deficiency that is significantly prevalent in developed countries as well [8]. Underutilized crops like African leafy vegetables (amaranth, moringa, and spider plant), orange-fleshed sweet potato (OFSP), and snake tomato (*Trichosanthes cucumerina*) contain diverse essential nutrients, including high-quality proteins, dietary fibers, vitamins, minerals, antioxidants [20], and bioactive compounds.

Amaranth (*Amaranthus viridis L.)* is a widespread weed occasionally cultivated like vegetables for their nutritive purposes in Nigeria, Gabon and DR Congo [28] and called Tete a tetedaye by the Yoruba natives in Nigeria. They are erect to ascending annual or short-lived perennial herbs that can grow up to 1 m tall with glabrous, angular stems bearing slender branches that are sparsely pubescent in the upper part, having multicellular hairs [28]. It contains high squalene and tocotrienol, along with other antioxidants that support glucose metabolism and alleviate oxidative stress [33, 29]. It also provides lysine, an essential amino acid often lacking in other grains, bioactive peptides and fibers that contribute to blood glucose regulation and improved lipid profiles [59], making amaranth a promising food for diabetes management, in Côte d'Ivoire, the leaf sap is used to treat eye infections, convulsions and epilepsy in children [28]. Reference [90] evaluated the antioxidant activities of extracts from amaranth grain using three different solvents (water, 50% ethanol and 100% ethanol), which suggests that their antioxidant properties make them useful as dietary antioxidants in food [75]. The ability of *A. viridis* to scavenge free radicals and reactive oxygen species has been attributed to its potential to overcome conditions such as oxidative stress, blindness, anaemia and age-related diseases [28]. A case study of five genotypes of the vegetable amaranth: AT3, AT7, AT11, and AT15, reported a moisture content that varied from 81.79 to 88.56 g/100 g FW (fresh weight), protein content from 5.05 to 5.55 g/100 g FW, and the carbohydrate level from 2.21 to 7.07 g/100 g FW [69, 70]. The energy value ranged between 28.95 and 58.47 kcal/100 g, while the digestible fibre content varied between 7.26 and 10.03 g/100 g FW. AT15 had the highest potassium level of 6.68 mg/g, while AT3 had the highest calcium content of 2.48 mg/g. The micronutrient concentration ranged from 10.96 to 17.26 μg/g Fe and 6.68 to 0.54 μg/g Mn. Another study on Amaranth grains reported a carbohydrate content of 40.5–87.1%, protein (12.7–19.8%), crude fibre (2.4–5.8%), fat (1.7–10.3%), and ash content of 2.2–3.5% [40]. Reference [3] evaluated the phytochemical content of five grain amaranth species, and the study showed that tannin level varied between 0.10 and 0.14 g/100 g, where *A. Caudatus* had the highest content, and *A. hybridus* exhibited the lowest. The phytate concentration ranged between 1.16

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and 1.58 g/100 g, with *A. hybridus* having the highest level and *A. caudatus* having the lowest. The total flavonoid concentration varied between 8.91 and 9.93 mg Catechin Equivalent (CE)/100 g, with *A. cruentus* having the highest level and *A. caudatus* having the lowest. The total polyphenol content ranged between 27.52 and 30.79 mg Gallic Acid Equivalent (GAE)/100 g, with *A. hybridus* having the highest concentration and *A. caudatus* having the lowest. Reference [69, 70] reported β-carotene concentration of 925.76 µg/g FW and vitamin C content of 693.56 mg/100 g FW in the twelve accessions of *A. hybridus*; these attributes make amaranth a promising vegetable.

Moringa (*Moringa oleifera L.*) belongs to the family *Moringaceae* and is commonly referred to as the "tree of life" or "miracle tree", horseradish or drumstick tree", and famously called okwe or okwe-oyibo in the Igbo speaking part of Nigeria, is a versatile plant recognized for its pharmacological properties and potential benefits against various diseases like ulcers, liver disease, heart disease, and cancer [57, 13] thus, widely grown as a medicinal and food source [89]. Most of the parts of this plant (root, leaves, fruit, bark, seeds, and flowers) are disclosed to have antitumor, antipyretic, anti-inflammatory, diuretic, cholesterol-lowering, antidiabetic, antioxidant, antispasmodic, antibacterial, and antifungal activities [13, 79]. It also contains glucosinolates and phenolic acids and has shown significant potential in regulating blood sugar levels, enhancing insulin secretion, and improving glucose uptake [7]. Moringa leaves are exceptionally nutrient-dense, containing high levels of vitamins (A, C, and E), calcium, iron, potassium, and protein, which support overall health and combat nutritional deficiencies common in diabetic patients. Its leaf powder is commonly used as a supplement [4]. Folate is a water-soluble vitamin B molecule that belongs to the B vitamin family. Its deficiency has serious metabolic and clinical effects [44]. Moringa is a good source of folate and has better bioavailability than other vegetables [68]. The major types of folate found in *Moringa oleifera*, according to a study, are 5-formyl-5,6,7,8-tetrahydrofolic acid (502.1µg/100g dry weight) and 5,6,7,8-tetrahydrofolic acid (223.9µg/100g dry weight). Reference [81] reported that *M. oleifera* flavonoids such as myricetin (5.8 mg/g), quercetin (0.207 mg/g), and kaempferol (7.57 mg/g) are very effective against several chronic diseases, while gallic acid (1.034 mg/g dry weight) was the most abundant phenolic acid present in its dried leaves. It shows excellent gastroprotective activity against aspirin-induced ulcers in rats [26]. The leaf extracts of *M. oleifera* possess anti-cancer activity that can be used to develop new therapeutic drugs for breast and colorectal cancers [69, 70]. With its inhibitory activity on nitric oxide production, *M. oleifera* demonstrates potential anti-inflammatory activity [85].

The African spider plant (*Cleome gynandra*) is an annual, climate-resilient herb or vegetable belonging to the family *Cleomaceae*. It grows in regions with temperatures of 15 to 25°C under full sun exposure. It contains minerals and vitamins, hence, has huge potential in reducing micronutrient deficiencies [41]. The African spider plant is used as food and herbal medicine due to its high levels of β-carotene, α-tocopherols, folic acid, ascorbic acid, iron, and calcium. Reference [2] reported that the spider plant exhibits a nutritional composition that varies with season. The study showed that with exception of vitamin C (dry matter level; 33.33 mg/100g FW) was higher in dry season than in rainy season (24.33mg/100g FW) and protein levels (39.07 %) highest in dry season, the oxalic acid level was more elevated in rainy season (10.17 mg/100g DW) than in dry season (8.73 mg/100g DW), total sugar was 2.3 mg/100g DW and 5.09mg/100g DW in dry and in rainy season respectively while reduced sugar was 0.62mg/100g DW in dry season and 1.02mg/100g DW in rainy season, β-carotene was 17.99µg/100g FW in dry season and 110.26µg/100g FW in rainy season. Soluble and insoluble fiber values differ significantly between the seasons. The soluble fibers were lower in the dry season (13.33%) than in the rainy season (16%), while insoluble fibers were higher in the dry season (25.1%) than in the rainy season. Phosphorus, iron, and potassium contents were more elevated in the dry season than in the rainy season. Phosphorus (33.35 mg/100g DW in dry season and 4.19 mg/100g DW in rainy season), iron (23.93 mg/100g DW in dry season and 10.17mg/100g DW in rainy season) and potassium (109.38 g/100g DW and 58.96 g/100g DW in rainy season) whereas, Magnesium and calcium contents were more elevated in rainy season (15.08 g/100g DW) and (45.25 g/100g DW) than in dry season (7.28 g/100g DW and 22.65 g/100g DW) respectively. In addition to its phytochemical content, the African spider plant has demonstrated antifungal, anti-inflammatory, anticancer, antidiabetic, and immunomodulatory properties in vitro [27, 71, 74].

The OFSP (*Ipomoea batatas*) is a variety of sweet potato and a member of the *convolvulaceae* family of flowering plants [39]. It is a pro-vitamin A (β-carotene) bio-fortified root crop that was developed to diversify the sources and intake of pro-vitamin A [51]. Currently, demand and attention have been raised on OFSP due to its high concentrations of β-carotene and non-provitamin A carotenoids (NPVAC). Reference [34] reported that OFSP has high potential to address vitamin A deficiency by food-based intervention programs in targeted nations. The high protein content of OFSP makes it a valuable crop for enhancing nutrition and addressing vitamin A deficiency in areas where it is prevalent [34, 23]. Additionally, OFSP is a valuable source of specific minerals, non-digestible dietary fibre, and antioxidants [16, 65]. As reported by three studies, OFSP has a moisture content that ranges from (64.5 – 72.96 % wet base) [49, 43, 65], protein content (1.91 – 3.69 %), fat (0.42 – 1.7 %) [49, 43, 65], starch (65.41 %) [65], crude fiber (0.35 – 3.68 %) [49, 43, 65], carbohydrate (21.10 – 90.17 %) [49, 43, 65]. Reference [77] reported that OFSP contained (13.11µg/g db) α – carotenoid and (48.66 µg/g db) β – carotenoid.

Trichosanthes cucumerina is a tomato – like fruit which belongs to the family of *Cucurbitaceae*. This annual climber plant, commonly known as Snake gourd, Snake tomato, serpent vegetable, long tomato or 'Tomato elejo or Tomati elegede' in Yoruba-speaking areas of the South-western, Daddar albasa in some Hausa Northern markets, and Ejula in certain Igbo communities of Nigeria, derives its name from the snake - like shape of the fruit. It is consumed as a

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vegetable due to its good nutritional value [88]. Its abundant functional constituents - flavonoids, carotenoids, phenolic acids, soluble and insoluble dietary fibers, and essential minerals- make the plant pharmacologically and therapeutically active [67, 12]. The plant contains carbohydrates, fat, fiber, proteins, minerals, and vitamins A and E at high levels. The predominant mineral elements are potassium (121.6mg/100g) and phosphorus (135 mg/100g), while magnesium, sodium, and zinc are also found in fairly high amounts [67]. *T. cucumerina* has been used in ancient therapy for headaches, alopecia, fever, abdominal tumors, bilious, boils, acute colic diarrhoea, haematuria, and skin allergies. The whole plant parts - fruits, leaves, roots, and seeds- have been reported to show medicinal properties such as antidiabetic, antibacterial, anti-inflammatory, anthelmintic, antifebrile, gastroprotective, and antioxidant activity [67, 12]. Reference [12] reported that the pulp of morphotypes of this plant (Morphotype I (V1), which has long fruit with a deep green background and white stripes, and Morphotype II (V2), which has light green coloured long fruit) had dry matter contents of 10.9 and 9.6 g/100 g fresh weight (FW), respectively, ascorbic acid contents of 25.7 and 24.8 mg/100 g fresh weight (FW), and lycopene concentrations of 18.0 and 16.1 mg/100 g FW. V2 had 46.8 percent more total phenolics, 78.0 percent more total flavonoids, and 26.2 percent more total ferric reducing antioxidant power (FRAP) than V1 ($P < 0.05$). The study also reported that V1 and V2 had carotene concentrations of 10.3 and 10.7 mg/100 g FW, with lutein making up the majority of the carotenoids with concentrations of 15.6 and 18.4 mg/100 g FW for V1 and V2, respectively. These phytochemicals play a significant role in the antibacterial properties, leading to the vulnerability of *E.coli* and *P. aeroginosa* to the action of *T.cucumerina* extracts used in the study, thereby suggesting that the two morphotypes of *T. cucumerina* have excellent nutraceutical qualities [12]. *T. cucumerina* can be considered a nourishing food commodity that possesses significant nutritional and functional benefits for human health.

These crops exhibit significant antioxidant activity, which can be attributed to their phenolic acids and carotenoid content [50]. By systematically characterizing the phytochemical composition of these crops, compounds with nutraceutical potential can be identified, thereby creating opportunities for dietary interventions against micronutrient deficiencies and chronic diseases.

III. PROCESSING TECHNOLOGIES FOR BIOACTIVE RETENTION

The successful transformation of underutilized crops into value-added products depends on processing techniques that retain their bioactive integrity. Drying techniques such as freeze-drying and hot-air drying affect carotenoid and polyphenol stability differently, with freeze-drying generally preserving higher concentrations [50]. Fermentation increases bioavailability of bioactives by breaking down complex phytochemicals, enhancing antioxidant capacity and probiotic potential. It significantly improves the nutritional profile of foods by increasing the levels of essential vitamins, probiotics, and amino acids [52]. Extrusion cooking process allows the incorporation of underutilized crop flours into cereal-based products, enhancing nutritional quality [1]. Emerging non-thermal technologies such as high-pressure processing (HPP) and pulsed electric field (PEF) are promising for preserving sensitive vitamins and phytochemicals while extending shelf life [15].

- HPP plays a crucial role in advanced food processing technologies, offering a significant advantage in quality retention and microbial safety. It is governed by three fundamental principles, including the principle of microscopic ordering, the isostatic principle, and Le Chatelier’s principle [9]. The high-pressure processing employs intense pressure on the microbial cell walls, causing irreversible damage and resulting in a decrease in microbial load. Conversely, the extreme pressure applied during processing also causes enzyme denaturation, thereby preventing enzymatic spoilage [61]. Thus, an acceptable pressure limit may be optimized with mild to moderate heat to effectively extend shelf life, as well as retention of bioactive compounds in liquid foods.
- Pulsed electric field (PEF) operates on the principle in which a liquid food is pumped through a pulse-generating system, where high-voltage input pulses create an electrical potential difference across the liquid food held between two electrodes [48]. It is a combination of high-voltage pulses (20 to 80 kV cm^{-1}) and electric field, significantly employed for pasteurizing liquid foods, which greatly reduces the microbial load present in liquid foods. The strength of the electric field and treatment time are the two key factors that significantly affect the processing efficacy of PEF. The exposure of PEF disrupts the cell membrane by inducing electrochemical instability, leading to the release of cell constituents and subsequent microbial death [10].
- Ultrasound treatment (sonication) employs sound waves with frequencies exceeding 20 kHz, which immediately transfers acoustic energy to the product during the ultrasound treatment [82]. This technology serves as an alternative to traditional thermal processing for the sterilization and pasteurization of liquid foods, which can be employed either by direct application using an ultrasonic probe or by immersing liquid food in an ultrasonic bath. The microbial killing mechanism is primarily due to the production of free radicals, thinning of cell membranes, and localized heating. The transmission of ultrasound in a liquid food generates bubble cavitation as a result of pressure fluctuation. The collapse of resultant micro-bubbles induces a localized rise of pressure and temperature. Consequently, the intense high pressure and local energy yield a pasteurization effect without significantly increasing the overall temperature [46, 37].

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