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Review Article

Viral Pathophysiology and Post-harvest Vitamin A Erosion Implications for Pediatric Retinol Status in Biofortified Sweetpotato Systems

Ekpor Anyimah-Ackah*

Department of Food and Nutrition Education, Faculty of Health, Allied Sciences and Home Economics Education, University of Education, Winneba, Ghana

Abstract

Background: Orange-fleshed sweetpotato (OFSP) is promoted as a biofortified crop for reducing vitamin A deficiency among children and women in low-resource settings. Its public health value depends on the whole delivery chain, from virus-free planting material and genotype selection to processing, storage, preparation, and consumption. Previous versions of the evidence narrative have sometimes implied that sweetpotato virus disease (SPVD) directly destabilizes carotenoids. The available literature supports a more cautious interpretation: SPVD is a proven agronomic and seed-system threat, while post-harvest handling is the strongest demonstrated driver of carotenoid erosion.

Objective: This critical review evaluates whether, how, and at what point's viral pathophysiology and post-harvest processes compromise the quantity, retention, bioaccessibility, and pediatric vitamin A value of OFSP systems.

Methods: Evidence was synthesized from selected peer-reviewed articles, thesis evidence, and technical guidance on OFSP efficacy, SPVD, genotype-by-environment performance, carotenoid chemistry, processing retention, storage stability, puree value chains, and scaling. Claims were classified as directly supported, indirectly supported, or unresolved.

Findings: Regular intake of boiled and mashed OFSP can improve vitamin A status in children, and 100-125 g of cooked OFSP can contribute substantially to the daily vitamin A needs of young children under suitable conditions. Carotenoid content varies markedly by genotype, location, flesh color, and environment. Boiling and steaming generally show high carotenoid retention, whereas baking, frying, sun drying, poor flour storage, and prolonged storage at ambient temperature can cause substantial losses. Storage studies consistently identify oxygen exposure, temperature, water activity, packaging, and duration as major determinants of provitamin A loss. SPVD and related viral infections reduce productivity, threaten seed systems, and may indirectly lower vitamin A delivery by reducing the availability and quality of marketable roots; however, direct evidence that SPVD causes carotenoid degradation or impaired bioavailability remains limited.

Conclusion: OFSP remains a credible crop-based strategy for vitamin A deficiency control, but its nutritional effect is not an intrinsic property of orange roots alone. It is the outcome of an integrated food system. The most defensible pathway links clean seed systems, SPVD-resistant and high-beta-carotene genotypes, high-retention processing, oxygen- and light-protective storage, appropriate dietary fat and nutrition education. Future studies should directly compare virus-infected and virus-free OFSP genotypes for carotenoid biosynthesis, retention, bioaccessibility, and child retinol outcomes.

More Information

***Corresponding author:** Ekpor Anyimah-Ackah, Department of Food and Nutrition Education, University of Education, Winneba, Ghana, Email: eaackah@uew.edu.gh

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Keywords: Orange-fleshed sweetpotato; Sweetpotato virus disease; Beta-carotene; Carotenoid retention; Biofortification; Pediatric vitamin A; Post-harvest physiology; SPVD

Introduction

Vitamin A deficiency remains a major public health concern in settings where diets are dominated by starchy staples and where access to animal-source foods, fortified products, and regular supplementation is inconsistent. The biological consequences of inadequate vitamin A include impaired visual function, reduced immunity, poor growth, and increased vulnerability to infection. For children, the risk is especially serious because rapid growth and repeated infections raise physiological requirements while diets are often monotonous and low in preformed retinol.

OFSP was developed and scaled as a practical biofortification response to this problem. Unlike white-fleshed sweetpotato, OFSP storage roots accumulate beta-carotene, the principal provitamin A carotenoid. Controlled feeding evidence shows that daily consumption of boiled and mashed OFSP can improve vitamin A status in primary school children. In the South African efficacy study, children aged 5-10 years consumed 125 g boiled and mashed OFSP for 53 school days, delivering approximately 1031 retinol activity equivalents per day as beta-carotene; the intervention improved vitamin A liver stores compared with white-fleshed sweetpotato [1]. Programmatic reviews also emphasize that a small cooked root of medium-intensity OFSP can meet the daily vitamin A needs of a young child when adequately retained and consumed [20,23].

The strength of OFSP as a public health tool is its fit with farming systems, food habits, and household production. Sweetpotato is already established as a food security crop in much of sub-Saharan Africa. It tolerates marginal environments better than many staples, can provide energy during seasonal scarcity, and can be integrated into household gardens, markets, and processed products [20,21]. However, the same characteristics that make OFSP promising also create vulnerability. The nutritional effect of OFSP depends on agricultural health, cultivar performance, post-harvest handling, processing, storage, preparation, and dietary context. A root with high beta-carotene at harvest may deliver far less vitamin A after viral stress, poor storage, flour oxidation, prolonged heating, or low-fat consumption.

This review responds to the need for a more mechanistically cautious and critically organized synthesis. The central research question is: to what extent does sweetpotato viral pathophysiology influence provitamin A accumulation, retention, bioaccessibility, and pediatric vitamin A outcomes in OFSP-based food systems? This question requires separating direct evidence from inference. The available literature strongly documents severe yield and seed-system effects of SPVD and related virus infections [11,22]. It also strongly documents carotenoid losses during storage and processing [2-7,14-16]. It does not yet establish, with equal strength, that SPVD directly destabilizes carotenoid-protein complexes or causes post-harvest carotenoid degradation. Therefore, this review treats SPVD as a demonstrated productivity and root-health threat and treats direct SPVD-carotenoid degradation as a research gap rather than a settled mechanism.

Review approach and evidence classification

This manuscript is a critical narrative review. The evidence base included clinical efficacy evidence, food composition studies, genotype-by-environment trials, processing and storage experiments, puree and bread technology studies, scaling literature, and sweetpotato virus studies. The review was organized around the OFSP vitamin A delivery chain: genotype and crop health, root carotenoid accumulation, post-harvest retention, food preparation, bioaccessibility, consumption, and child vitamin A status.

To preserve citation fidelity, each claim was classified into one of three categories. A claim was considered directly supported when the cited study measured the relevant outcome, such as beta-carotene retention during boiling or infection of root sprouts. A claim was considered indirectly supported when the evidence measured a related upstream or downstream outcome, such as SPVD response and yield, as threats to vitamin A delivery. A claim was considered unresolved when it required mechanistic evidence not directly measured in the available works, such as virus-induced destabilization of carotenoid sequestration structures in OFSP roots. This classification is important because the literature spans plant pathology, food chemistry, human nutrition, and implementation science, and overgeneralization across these fields can produce unsupported conclusions.

The review emphasizes evidence strength, methodological variability, and practical implications for biofortified sweetpotato systems. The purpose is not to argue that viral disease and post-harvest loss are equivalent mechanisms, but to clarify how each constrains the nutritional performance of OFSP interventions at different points in the value chain.

OFSP as a vitamin A delivery system

The nutritional rationale for OFSP is well established. Beta-carotene is converted to retinol in humans and is the dominant provitamin A carotenoid in most orange storage roots. In raw and processed OFSP, all-trans-beta-carotene is commonly the major carotenoid form, although heat processing can promote cis-isomer formation [3,8]. The all-trans form has a higher provitamin A value than the cis forms, which makes both total concentration and isomer profile relevant to nutritional quality.

Clinical evidence provides the endpoint anchor. The South African randomized school-feeding study demonstrated that a daily portion of boiled and mashed OFSP improved vitamin A status compared with white-fleshed sweetpotato [1]. This establishes that beta-carotene in OFSP can be bioefficacious under controlled dietary conditions. However, it does not prove that all OFSP varieties, products, or storage systems deliver the same benefit. Delivery depends on concentration at harvest, retention after processing, bioaccessibility in the meal, and the physiological status of the child.

Scaling evidence reinforces the importance of integrated agriculture-nutrition design. OFSP adoption in sub-Saharan Africa required not only breeding but also seed systems, nutrition education, market development, and attention to consumer preferences. The Sweetpotato for Profit and Health Initiative and related investments reached millions of households, but success depended on locally adapted varieties, demand creation, and institutional support [20,21]. Thus, OFSP should be understood as a food-system intervention, not merely as a high-carotenoid crop.

Genotype, environment, and carotenoid variability

One of the strongest findings across the corpus of available literature is that OFSP nutritional value is genotype-dependent. Alam and colleagues analyzed nine Bangladeshi OFSP varieties and found total carotenoids ranging from 0.38 to 7.24 mg per 100 g fresh weight, while total polyphenols ranged from 94.63 to 136.05 mg gallic acid equivalent per 100 g fresh weight [9]. Islam and colleagues similarly reported intra-varietal differences in carotenoid, trans-beta-carotene, and cis-beta-carotene concentrations in raw and boiled OFSP samples, with Kamalasundari and BARI SP-5 showing higher beta-carotene [8]. These differences mean that simple classification as orange-fleshed is insufficient for predicting vitamin A value.

Recent studies sharpen this point. In Australian-grown cultivars, Bellevue, New Orleans, and Beauregard contained substantially higher beta-carotene than white- or purple-fleshed cultivars, while the white skin purple flesh cultivar had stronger phenolic and antioxidant profiles but negligible beta-carotene [13]. In northern Ethiopia, Lamaro and colleagues demonstrated that nutritional traits varied by genotype, location, and genotype-by-environment interaction; Ininda, Gloria, and Amelia were superior for several yield and nutraceutical traits, including beta-carotene and dry matter [10]. In a 2024 multi-environment Ethiopian trial, G8 (Cacilia-22) combined yield stability, dry matter, beta-carotene advantage, and low SPVD reaction score, suggesting that nutritional and plant-health traits can be selected together [11].

The 2026 Frontiers in Plant Science germplasm study further demonstrates that beta-carotene accumulation and marketable root traits are dynamic and germplasm-specific. Qingyushu No.6, Yushu615, and Yuhongxinshu No.3 maintained different beta-carotene levels, and dense planting increased the medium-sized storage root rate to over 70%, reaching 87.13% in some conditions [12]. Although this study was not focused on African VAD programs, it is important because it shows that nutritional density, root size distribution, and commercial value can be integrated in breeding and agronomy decisions. For public health nutrition, this means that selection should not prioritize beta-carotene alone; it should also include dry matter, yield stability, disease response, consumer preference, storage behavior, and processing suitability.

Sweetpotato virus disease and viral pathophysiology

SPVD is a major threat to sweetpotato production, particularly where vegetative propagation and informal seed systems allow viral accumulation across seasons. The disease is typically associated with synergistic infection involving Sweet potato feathery mottle virus and Sweet potato chlorotic stunt virus, although several other viruses can occur in sweetpotato systems. The agronomic consequence is severe because infected vines and roots can serve as reservoirs, and farmers frequently recycle planting material from previous crops or from neighboring fields.

The strongest virus-specific evidence in the uploaded corpus concerns infection movement and seed-system risk. Adikini and colleagues showed that storage roots can be virus reservoirs. More than 70% of sprouts from roots selected after harvest were infected, and roots obtained from symptomless plants also produced infected sprouts at substantial rates in some locations. Dual infection produced symptomatic sprouts, whereas reversion occurred only in sprouts singly infected with Sweet potato feathery mottle virus [22]. This evidence directly supports the need for clean planting material, continuous seedstock sanitation, and farmer training in virus recognition and seed selection.

Recent breeding evidence suggests that SPVD response can be integrated with yield and nutritional traits. Gurmu and colleagues evaluated ten OFSP genotypes across Ethiopian locations and reported highly significant genotype and location effects. G8 (Cacilia-22) outperformed other genotypes for root yield, dry matter, and beta-carotene, and had a low SPVD reaction score of 1.17 on a 1-9 scale, placing it in the resistant range [11]. This is important because it moves the discussion from disease avoidance alone to integrated breeding for agronomic, nutritional, and disease-resistance performance.

The critical point for this review is the evidence hierarchy. Viral infection is clearly a productivity, seed-system, and crop-health problem. It can reduce the amount of OFSP available, threaten varietal performance, and reduce the reliability of the biofortification pipeline. However, the uploaded evidence does not directly demonstrate that SPVD degrades beta-carotene, destabilizes carotenoid-protein complexes, or reduces carotenoid bioaccessibility after cooking. Those hypotheses are biologically plausible because plant stress can alter source-sink relationships, root development, and storage-root physiology, but they remain insufficiently tested in OFSP. Therefore, the defensible wording is that SPVD may indirectly threaten vitamin A delivery through yield loss, poor root quality, and seed degeneration, while direct effects on carotenoid metabolism require targeted experimental confirmation.

Carotenoid chemistry and mechanisms of post-harvest erosion

Carotenoids are chemically vulnerable molecules because their extended conjugated double-bond systems, which give them color and biological activity, also make them susceptible to oxidation, isomerization, and photodegradation. De Moura and colleagues summarize that degradation can be driven by oxygen, light, heat, water activity, metals, enzymes, and free radicals, and that processing disrupts tissue barriers that normally protect carotenoids within the plant matrix [6]. The same principle underlies OFSP storage and processing losses: once roots are cut, dried, milled, heated, or exposed to air, carotenoids become more accessible to degradation reactions.

The Bechoff drying and storage studies provide the most important mechanistic evidence for OFSP post-harvest erosion. In Uganda, drying losses in chips were generally modest, often 15% or less, but four-month storage losses were approximately 70% [4]. The doctoral work extended this evidence by showing that storage losses could reach 70-80% in field settings and that oxygen was the main degradation driver, followed by temperature. Degradation followed first-order kinetics, and volatile products linked to beta-carotene breakdown were identified [5]. This body of evidence strongly supports the conclusion that storage, rather than drying alone, is a major bottleneck in dried OFSP products.

Retention evidence is also strongly method-dependent. De Moura and colleagues reported sweetpotato drying retention of 66-96%, boiling and steaming retention of 80-98%, baking retention of 30-70%, and frying retention of 18-54%, while noting that flour storage can fall to as low as 20% after 1-4 months [6]. Vimala and colleagues found oven drying and boiling to be relatively protective, with beta-carotene retention of 89-96% for oven drying and 84-90% for boiling, while sun drying showed lower retention of 63-73% [7]. These values should not be treated as universal constants because they depend on cultivar, sample preparation, analytical method, true-retention calculation, temperature, surface area, oxygen exposure, and storage duration.

Cooking studies illustrate why true-retention methodology matters. Van Jaarsveld and colleagues measured beta-carotene retention in boiled and mashed Resisto OFSP using paired samples and true retention calculations that accounted for weight change, moisture, and soluble solids. True retention reached 92% when medium-sized roots were boiled for 20 min with the lid on, 88% when boiled for 30 min without the lid, and 70-80% when different root sizes were boiled for 30 min [2]. Bengtsson and colleagues reported that all-trans-beta-carotene was the major provitamin A carotenoid in improved OFSP cultivars and that boiling, steaming, and deep-frying had retentions around 77-78%, while drying losses were modest under experimental conditions [3]. These studies support boiling and steaming as generally high-retention preparation methods, while also showing that processing changes isomer profiles and extractability.

Storage systems, packaging, and processed products

Fresh-root storage, flour storage, dried chips, and processed foods all present different retention profiles. Tumuhimbise and colleagues showed that storage conditions altered beta-carotene content, bioaccessibility, and tissue microstructure. Pit storage at lower temperature and high relative humidity retained more beta-carotene and higher in vitro bioaccessibility than ambient and dark-room storage, whereas warmer conditions increased cell wall lignification and reduced the bioaccessible fraction [14]. This finding is important because nutritional value depends not only on total carotenoid concentration but also on the fraction potentially released during digestion.

Flour storage is particularly vulnerable because milling increases surface area and oxygen exposure. Chilungo and colleagues found significant carotenoid losses in OFSP flour under both light and dark conditions. Kraft paper had the greatest carotenoid loss, 59.33%, while aluminum foil laminate had the lowest loss, 29.88%, and water activity increased across packages [15]. This supports the practical recommendation that OFSP flour should be stored in packaging that limits oxygen, light, and moisture. However, even improved packaging did not eliminate loss, so storage duration should be minimized, and product turnover should be planned.

Processed syrups also show substantial micronutrient decline. Irakiza and colleagues developed OFSP syrup and pulp-syrup products and observed marked losses in beta-carotene and vitamin C over 56 days. Pulp syrup beta-carotene declined from 2.25 mg per 100 g to 0.70 mg per 100 g at 4 C and 0.51 mg per 100 g at 25 C, while syrup declined from 2.20 mg per 100 g to 0.47 and 0.34 mg per 100 g under the same temperatures [16]. This study reinforces two principles: cooler storage preserves carotenoids better than room temperature, and processing innovation must be evaluated for nutrient stability, not only sensory acceptability.

Puree and bakery systems provide promising but not universal solutions. Wanjuu and colleagues found that bread with 30% OFSP puree had a beta-carotene value and longer shelf-life than white bread, spoiling on day six compared with day four for white bread, although beta-carotene and color declined with storage temperature and time [17]. Owade and colleagues reviewed OFSP puree bread and noted that puree can substitute wheat flour, improve beta-carotene delivery, and support value chains, but cold-chain dependence, inconsistent puree supply, and scalability remain constraints [18]. The implication is that shelf-stable puree is a valuable complementary strategy, especially for markets and institutional feeding, but it should not be presented as the single superior solution for all contexts. Its performance must be compared with fresh roots, dried chips, flour, local recipes, and household-level feasibility.

Bioaccessibility, meal context, and pediatric retinol outcomes

The pathway from orange root to child retinol status is not linear. Harvested beta-carotene must survive storage and processing, be released from the food matrix during digestion, be incorporated into micelles, be absorbed, and be converted to retinol. This pathway is influenced by carotenoid isomer form, food matrix, cooking method, dietary fat, infection burden, and baseline vitamin A status. Consequently, total beta-carotene content alone can overestimate biological effect.

The efficacy study by van Jaarsveld and colleagues demonstrates that OFSP beta-carotene can improve vitamin A status in children when delivered consistently in an appropriate form [1]. However, that study used boiled and mashed OFSP under controlled school-feeding conditions. It did not test dried flour after four months of ambient storage, bread stored at high temperature, syrup after 56 days, or roots from virus-infected crops. Therefore, public health programs should not assume equivalence among all OFSP products. Each product should be evaluated for retained beta-carotene, isomer profile, where possible, bioaccessibility, and realistic intake.

Bioaccessibility evidence from storage studies suggests that root microstructure matters. Pit-stored roots retained higher beta-carotene and higher in vitro bioaccessibility than roots stored under ambient or dark-room conditions [14]. Processing can sometimes improve extractability by softening tissues, but it can also promote isomerization or degradation. This duality explains why apparent retention may exceed true retention in some studies: processing may make carotenoids easier to extract analytically even when absolute nutrient content has declined. Reviewers and program designers should therefore prioritize true retention and biologically meaningful endpoints.

Dietary context remains essential. OFSP should be promoted within meals that improve carotenoid absorption, including modest fat, where culturally and economically feasible. Nutrition education is therefore not an optional add-on; it is part of the biofortification intervention. Training materials emphasize OFSP utilization, processing, retention, and diverse recipes, including infant and young child feeding applications [23]. Scaling literature also shows that nutrition education helped create demand and translate crop adoption into dietary change [20,21].

Critical appraisal of current evidence

The evidence base is strong in some areas and weak in others. It is strong for pediatric efficacy under controlled feeding, genotype variability, processing retention, storage degradation, and the seed-system importance of viral infection [1-16,20-22]. It is weaker for direct mechanistic connections between SPVD and carotenoid metabolism. This distinction is the central scientific correction required for a credible review.

First, the literature establishes that SPVD and virus-infected planting material threaten productivity, but it does not yet quantify how SPVD changes beta-carotene biosynthesis or degradation in OFSP storage roots. Studies on virus movement show infection in root sprouts and limited reversion patterns [22], and genotype trials report SPVD reaction alongside yield, dry matter, and beta-carotene traits [11]. These studies justify clean seed and resistant genotype recommendations. They do not justify claims that SPVD directly destabilizes carotenoids unless additional biochemical evidence is provided.

Second, genotype variability complicates any universal claim. Darker orange flesh often indicates higher carotenoid concentration, but total nutritional value also depends on dry matter, yield, root size, environment, consumer preference, and retention after processing [9-13]. Breeding for beta-carotene alone may produce varieties that are agronomically weak, organoleptically unacceptable, or poorly retained during storage. Conversely, genotypes with excellent yield or dry matter but moderate beta-carotene may still contribute meaningfully if widely adopted and consumed regularly.

Third, retention estimates vary because methods vary. True retention requires paired raw and cooked samples and correction for weight, moisture, and soluble solids [2,6]. Apparent retention can mislead because processing may increase extraction efficiency. Studies also differ by cultivar, sample size, root size, cooking time, drying thickness, packaging material, and analytical method. Therefore, Tables of retention values should be interpreted as ranges rather than fixed constants (Tables 1-3).

Fourth, the strongest demonstrated mechanism of vitamin A erosion is post-harvest exposure to oxygen, temperature, water activity, light, and time [4-6,14-16]. This evidence is more direct than the evidence for viral effects on carotenoid stability. Programs that focus only on high-beta-carotene cultivars but neglect storage and packaging may lose much of the intended nutritional advantage before consumption.

Finally, scalability is not only technical. OFSP adoption depends on seed availability, market incentives, gendered labor, consumer preference, product affordability, processing infrastructure, and institutional support [18,20,21,23]. A technically excellent puree system may fail if cold-chain or packaging costs are prohibitive. A high-retention fresh-root strategy may fail if planting material is virus-infected. A

Table 1: Evidence classification for major claims

Claim	Evidence status	Evidence basis	Recommended interpretation
OFSP consumption can improve child vitamin A status	Directly supported	Randomized feeding study and scaling syntheses [1,20,23]	Regular consumption of adequately retained OFSP can improve vitamin A status under suitable dietary conditions.
SPVD is a threat to vitamin A delivery	Indirectly supported for nutrition; directly supported for crop health	Virus movement and genotype/SPVD response studies [11,22]	SPVD threatens delivery mainly through yield, root health, and seed-system degeneration.
SPVD directly degrades carotenoids	Unresolved	Uploaded studies do not directly measure virus-induced carotenoid degradation.	Present as a research gap, not a settled mechanism.
Storage causes major carotenoid loss.	Directly supported	Drying/storage, flour, syrup, and root storage studies [4-6,14-16]	Storage is among the strongest demonstrated points of provitamin A erosion.
Puree is the single best intervention.	Overstated if universal	Puree and bread evidence is product-specific [17,18]	Treat puree as a promising complementary strategy, not a universal solution.

Table 2: Processing and storage implications for carotenoid retention in OFSP systems

Product or method	Key retention finding	Main risk factor	Program implication	Sources
Boiled and mashed roots	True retention often high; 92% under favorable 20 min boiling conditions	Longer boiling, root-size variability, lixiviation	Promote boiling/steaming with standardized recipes	[2,3,6,7]
Dried chips	Drying losses are often modest, but storage losses can reach about 70% after four months.	Oxygen, temperature, duration	Prioritize storage protection and rapid turnover	[4,5]
OFSP flour	Losses occur across packaging; Kraft paper is worse than aluminum foil laminate.	Surface area, oxygen, moisture, light	Use oxygen/light/moisture barriers and monitor shelf-life	[15]
Syrup products	Beta-carotene and vitamin C decline markedly over 56 days	Temperature and duration	Do not assume processed products remain nutritionally stable	[16]
Puree bread	30% puree bread had beta-carotene and a longer shelf-life than white bread	Temperature, product formulation, supply chain	Useful value-chain option with product-specific testing	[17,18]
Fresh root storage	Pit storage retained more beta-carotene and bioaccessibility than ambient storage.	Heat, lignification, and physiological deterioration	Improve low-temperature storage and handling	[14]

Table 3: Future research agenda linking plant pathology, food chemistry, and pediatric nutrition.

Research gap	Recommended study design	Core measurements	Expected contribution
Direct SPVD-carotenoid link	Controlled infected vs virus-free genotype trial	Yield, dry matter, carotenoid profile, gene expression, bioaccessibility	Determine whether SPVD directly changes provitamin A quality.
Retention under real value chains	Household and market storage trials	Temperature, oxygen, water activity, packaging, true retention	Translate laboratory retention into practical storage guidance.
Bioaccessibility of stored products	In vitro digestion and feeding studies	Micellarized beta-carotene, meal fat, isomer profile	Connect the retained carotenoid to potential absorption.
Clinical effect of processed OFSP	School or community intervention trials	Product intake, retained beta-carotene, and child retinol indicators	Verify whether processed products improve vitamin A status.
Adoption and equity	Mixed-method scaling studies	Cost, gender, labor, consumer preference, and seed access	Design interventions that are technically and socially feasible.

high-beta-carotene genotype may fail if consumers reject its texture. The public health effectiveness of OFSP is therefore a property of the integrated system.

Practical implications for plant science, phytopathology, and nutrition programs

For plant science and phytopathology, the priority is to treat nutritional quality as a breeding and disease-management trait. SPVD resistance, clean seed supply, and virus surveillance should be integrated with beta-carotene, dry matter, yield stability, and consumer preference. The G8 (Cacilia-22) evidence from Ethiopia illustrates the possibility of combining yield, dry matter, beta-carotene, and low SPVD reaction in one genotype [11]. Similar multi-trait selection should be expanded to other agroecologies.

For post-harvest systems, the priority is to minimize oxygen, light, heat, and storage time. Fresh roots should be stored under conditions that limit physiological deterioration. Dried chips and flour should be packaged with strong oxygen, light, and moisture barriers. Aluminum foil laminate performed better than Kraft paper for flour retention [15]. Dried products should not be held for prolonged periods without nutrient-loss monitoring, because storage losses can be far greater than drying losses [4,5].

For processing, boiling and steaming should remain preferred household methods where culturally acceptable, because they generally preserve carotenoids better than high-heat frying or baking [2,3,6,7]. Puree, bread, and other value-added products should be promoted only with product-specific nutrient retention and shelf-life data. When puree systems are used, the program should address microbial safety, packaging, supply continuity, affordability, and retained beta-carotene after storage [17,18].

For public health nutrition, OFSP should be embedded in behavior-change communication that explains portion size, preparation, fat-assisted absorption, and feeding frequency. The evidence that OFSP can improve child vitamin A status is compelling, but it depends on regular intake and retained carotenoid value [1,20,23]. Programs should therefore measure not only adoption and yield, but also product form, storage duration, retained beta-carotene, and child consumption.

Limitations of current knowledge

Several limitations constrain the present evidence base. First, direct studies comparing virus-infected and virus-free OFSP roots for carotenoid biosynthesis, carotenoid sequestration, post-harvest retention, and bioaccessibility are scarce. This prevents firm conclusions about direct SPVD effects on provitamin A quality. Second, many processing and storage studies use specific cultivars and controlled conditions, limiting generalization across African smallholder systems. Third, retention studies differ in analytical methods and true-retention calculations, complicating comparisons across studies [2,6]. Fourth, bioaccessibility and clinical efficacy are not routinely linked to post-harvest studies. A product may retain measurable beta-carotene but still vary in retinol impact depending on isomer profile, meal composition, and child health. Fifth, socioeconomic and gendered constraints are often discussed in scaling literature but are less often quantified alongside biochemical outcomes [20,21].

This review is also limited by its reliance on available published and available works. It does not include unpublished field data, direct laboratory reanalysis, or meta-analysis of raw datasets. Therefore, conclusions are framed as evidence-weighted synthesis rather than pooled quantitative estimates.

Future research priorities

Future research should address the missing mechanistic link between viral pathophysiology and carotenoid nutrition. Controlled trials should compare virus-free, singly infected, and dually infected OFSP plants of the same genotype, measuring root yield, dry matter, starch-sugar balance, total carotenoids, all-trans-beta-carotene, cis isomers, carotenoid biosynthetic gene expression, and post-harvest degradation kinetics. These studies should include both susceptible and resistant genotypes so that breeding programs can identify traits that protect both yield and nutritional density.

Second, post-harvest studies should be aligned with real value chains. Dried chips, flour, puree, bread, syrup, and boiled roots should be evaluated under household, market, and institutional feeding conditions. Key variables should include oxygen permeability, water activity, temperature, light exposure, package type, storage duration, root size, slice thickness, and cooking time. Studies should report both fresh-weight and dry-weight values, true retention, and, where possible, bioaccessible beta-carotene.

Third, nutrition studies should connect retained carotenoid to child outcomes. The strongest evidence comes from controlled feeding, but more implementation research is needed to determine how much vitamin A is actually delivered through routine household and school-feeding systems after realistic storage and processing. Biomarkers such as serum retinol, modified-relative-dose-response indicators, or other validated measures should be linked to dietary intake, product form, and infection status.

Fourth, scaling research should compare intervention packages. Clean seed plus nutrition education, resistant genotypes plus improved packaging, puree enterprise models, and household fresh-root strategies should be evaluated for cost, equity, gender burden, adoption, nutrient retention, and child intake. The goal should be not only to produce orange roots but to deliver bioavailable vitamin A reliably to vulnerable children.

Conclusion

OFSP remains one of the most credible food-based biofortification strategies for improving vitamin A intake in low-resource settings. Its value is supported by clinical evidence, high beta-carotene content in suitable genotypes, and successful scaling experience [1,20,21]. However, its public health effect depends on an intact delivery chain. Viral disease threatens the chain by reducing productivity, undermining seed systems, and limiting the availability of healthy roots [11,22]. Post-harvest processes threaten the chain by degrading carotenoids through oxygen, temperature, water activity, light, processing intensity, and time [4-6,14-16].

The most scientifically defensible conclusion is that SPVD is a proven indirect threat to vitamin A delivery, while post-harvest handling is the strongest directly demonstrated mechanism of provitamin A erosion. Direct SPVD-induced carotenoid degradation remains an important hypothesis, not a settled fact. A conceptual model should therefore avoid overstated causality and instead integrate plant pathology, breeding, food chemistry, and nutrition implementation.

Sustainable OFSP-based vitamin A programs should combine virus-free planting material, SPVD-resistant and high-beta-carotene genotypes, consumer-accepted dry matter and sensory traits, high-retention preparation methods, oxygen- and light-protective storage, shelf-stable product innovation where feasible, and nutrition education that supports regular intake and absorption. This integrated approach offers the best route for translating biofortified crop potential into measurable pediatric retinol benefit.

Declarations

Availability of data and materials

All evidence synthesized in this review was obtained from previously published literature and technical sources cited in the reference list. No new human, animal, or laboratory data were generated for this manuscript.

Author contributions

Ekpor Anyimah-Ackah conceptualized the review, synthesized the evidence, drafted and revised the manuscript, and approved the final version for submission.

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