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Effects of Processing Methods on Bioactive Compounds and Antioxidant Activity of African Leafy Vegetables: A Review

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Abstract

African leafy vegetables (ALVs) are important contributors to dietary diversity and food security in sub-Saharan Africa, providing essential micronutrients and bioactive compounds with antioxidant properties. However, these vegetables are highly perishable and undergo various processing treatments that can alter their nutritional and functional quality. This systematic review synthesizes evidence on the effects of processing methods on bioactive compounds and antioxidant activity in ALVs. A systematic search of Google Scholar, PubMed Central, Scopus, and Web of Science identified 16 studies meeting inclusion criteria, investigating approximately 23 leafy vegetable species subjected to cooking, blanching, drying, fermentation, and roasting. Thermal treatments such as steaming, stir-frying, and roasting most consistently increased measured phenolic content, likely through cell-wall disruption, enzyme inactivation, and Maillard reaction product formation. Fermentation also enhanced phenolic and flavonoid contents in some vegetables. Vitamin C and carotenoid responses were more variable, with freeze-drying retaining higher ascorbic acid concentrations while stir-frying improved carotenoid extractability and bioaccessibility. Antioxidant activity varied by assay, with FRAP, DPPH, and ABTS producing non-interchangeable results due to different analytical mechanisms. The review distinguishes between compound concentration, retention, extractability, and bioaccessibility, emphasizing that increased measured content does not necessarily indicate improved nutritional value. Processing outcomes were compound-specific, species-specific, and method-dependent, with no single method universally optimal for preserving all bioactive compounds. Key limitations included heterogeneous study designs, inconsistent reporting units, limited assessment of individual phenolic

compounds, and scarce evidence on bioaccessibility and human-relevant endpoints. Standardized processing conditions, consistent analytical methods, and inclusion of multiple outcomes within single experiments are recommended to support evidence-based processing recommendations for ALVs.

Keywords: African leafy vegetables, bioactive compounds, antioxidant activity, phenolic compounds, carotenoids, vitamin C, bioaccessibility

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Introduction

African leafy vegetables (ALVs) comprise diverse indigenous and traditional plant species that have long contributed to the diets, cultures, and food systems of communities across sub-Saharan Africa (Uusiku et al., 2010; Neugart et al., 2017; Shayanowako et al., 2021). They include amaranth (*Amaranthus* spp.), African nightshade (*Solanum* spp.), spider plant (*Cleome gynandra*), cowpea leaves (*Vigna unguiculata*), Ethiopian kale (*Brassica carinata*), jute mallow (*Corchorus olitorius*), and pumpkin leaves (*Cucurbita* spp.) (Neugart et al., 2017; Lugumira et al., 2025). These vegetables contribute to dietary diversity and food and nutrition security through their nutritional, cultural, and economic importance, as well as their adaptation to local agroecological conditions (Uusiku et al., 2010; Lugumira et al., 2025; Begouabe et al., 2026). They provide essential micronutrients, including provitamin A carotenoids, vitamins C and E, folate, iron, and zinc, although their nutritional contributions vary among species (Flyman & Afolayan, 2006; Uusiku et al., 2010). Their potential to support sustainable and climate-resilient food systems has further strengthened interest in conserving and utilising local agrobiodiversity (Kaseke et al., 2025; Shayanowako et al., 2021).

Beyond their essential nutrients, ALVs contain bioactive compounds that contribute to their antioxidant capacity and other functional properties (Uusiku et al., 2010; Neugart et al., 2017; Fioroni et al., 2023; Lugumira et al., 2025). These compounds include phenolics,

flavonoids, carotenoids, and chlorophylls, which differ in their chemical structures, stability, and responses to processing. Phenolics and flavonoids, including chlorogenic acid, caffeoylmalic acid, rutin, and kaempferol derivatives, exhibit antioxidant properties through mechanisms such as free-radical scavenging and metal chelation (Managa et al., 2019; Managa et al., 2020b; Arfaoui, 2021; Rudrapal et al., 2022). Carotenoids such as β-carotene, lutein, and zeaxanthin contribute to provitamin A activity and other physiological functions (Mashiane et al., 2022; Narra et al., 2024; Issa et al., 2025). Chlorophylls contribute to the characteristic green colour of leafy vegetables, whereas vitamin C is particularly susceptible to degradation through exposure to heat, oxygen, and light, as well as leaching into cooking water (Managa et al., 2020c; Ambra et al., 2023; Kinyi et al., 2022; Ejoh et al., 2021).

Despite their nutritional and functional value, ALVs are highly perishable, making processing important for preparation, preservation, and the reduction of postharvest losses (Cheptoo et al., 2019; Gogo et al., 2017). However, processing can alter their nutritional composition and bioactive compound profiles. Depending on the method and the characteristics of the vegetable, processing may increase the measured concentration or extractability of some compounds while reducing others. Understanding these changes is therefore essential for identifying processing methods that balance nutrient retention, food safety, shelf life, and sensory acceptability.

Evaluating these effects requires distinguishing between bioactive compound content and antioxidant activity, which are related but distinct measures of vegetable quality. Total phenolic content (TPC), total flavonoid content (TFC), and measurements of individual phenolic compounds or carotenoids quantify specific compounds or groups of compounds under defined analytical conditions (Arfaoui, 2021; Narra et al., 2024). In contrast, in vitro assays such as DPPH, ABTS, and FRAP estimate antioxidant activity through different analytical principles. The results are not directly interchangeable, and an increase in measured phenolic content does not necessarily correspond to a proportional increase in antioxidant activity (Narra et al., 2024; Fioroni et al., 2023). This distinction is particularly important when evaluating ALVs because processing responses may vary with species, tissue structure, cell-wall composition, maturity, growing conditions, and initial bioactive compound profiles (Cheptoo et al., 2019; Neugart et al., 2017; Palermo et al., 2014; Mwanri et al., 2018; Lugumira et al., 2025). Consequently, meaningful comparisons of processing methods require consideration of both the vegetable species and the specific outcome measured. Such comparisons can help clarify how processing influences bioactive compound retention and antioxidant activity and inform the selection of appropriate methods for different ALVs.

Processing is important for preparing and preserving ALVs

because these vegetables are perishable and undergo various treatments before consumption or storage (Cheptoo et al., 2019; Gogo et al., 2017). Common cooking methods include boiling, blanching, steaming, frying, stir-frying, roasting, and microwaving, while drying and fermentation are primarily used for preservation. Other approaches, including freeze-drying, solar-cabinet drying, and ultraviolet treatment, have also been investigated for maintaining quality and extending shelf life (Gogo et al., 2017; Managa et al., 2020c; Palermo et al., 2014; Misci et al., 2021; Stoll et al., 2021; Kaseke et al., 2025). Processing outcomes depend on factors such as temperature, treatment duration, water availability, oxygen exposure, and the use of oil or other ingredients. Moreover, experimental treatments may involve conditions that are not readily accessible to household and small-scale processors, making it important to consider both the processing method and its practical application (Managa et al., 2020b; Mashiane et al., 2022b; Ukom et al., 2023; Arfaoui, 2021; Narra et al., 2024). Although processing can improve palatability, extend shelf life, and reduce certain antinutritional factors, it may also cause nutrient losses or alter bioactive compounds. These changes can affect the nutritional and functional quality of ALVs, highlighting the need for evidence-based processing recommendations that balance compound retention, food safety, preservation, and sensory acceptability.

Processing can alter bioactive compounds through several mechanisms that may occur simultaneously. Heat, oxygen, light, and changes in pH can promote the degradation of sensitive compounds, including vitamin C and some carotenoids and phenolic metabolites. Water-based treatments may also cause water-soluble compounds to leach into cooking water, reducing the amounts retained in the vegetable when the liquid is discarded (Palermo et al., 2014; Narra et al., 2024; Kinyi et al., 2022; Managa et al., 2019). Conversely, thermal treatment may inactivate endogenous enzymes involved in the oxidation of phenolic compounds, while heating and other forms of tissue disruption can release compounds previously bound within the plant matrix, increasing their extractability during analysis (Arfaoui, 2021; Palermo et al., 2014; Marrufo-Hernández et al., 2024). Drying may also increase the measured concentration of some compounds on a weight basis because moisture is removed, even when the absolute amount of a compound has not increased (Managa et al., 2020c). Fermentation may modify the plant matrix through microbial activity and enzymatic reactions, potentially changing the release and transformation of phenolic compounds and flavonoids (Irakoze et al., 2023b; Septembre-Malaterre et al., 2018). In addition, processing may influence bioaccessibility, which refers to the fraction of a compound released from the food matrix during digestion and potentially available for absorption. However, greater

extractability or higher measured concentration should not automatically be interpreted as greater bioaccessibility or a corresponding increase in biological effects (Arfaoui, 2021; Palermo et al., 2014; Narra et al., 2024).

Variations in bioactive compounds across African leafy vegetables reflect differences in their secondary metabolite profiles and tissue structure (Neugart et al., 2017). Plant cell walls contain cellulose, hemicellulose, and pectin, while some tissues also contain lignin. These components influence the binding and extractability of bioactive compounds, including hydroxycinnamic acids associated with cell-wall structures (Arfaoui, 2021; Palermo et al., 2014). Processing can alter the plant matrix through several mechanisms: heat softens tissues, mechanical forces rupture cells, acidic or alkaline conditions may modify cell-wall components, and microbial enzymes during fermentation may release bound compounds or transform them into other metabolites (Palermo et al., 2014; Arfaoui, 2021; Irakoze et al., 2023b; Septembre-Malaterre et al., 2018). However, increased release or extractability does not necessarily indicate improved retention, as these changes may occur alongside degradation or oxidation. Consequently, processing outcomes depend on the vegetable species, compound type, processing method, and treatment conditions, helping explain variations in findings across studies.

Previous reviews have examined the effects of processing on vegetable phytochemicals and antioxidant activity (Palermo et al., 2014; Arfaoui, 2021; Narra et al., 2024), while others have focused on the nutritional value, phytochemical composition, and food-system contributions of African leafy vegetables (Uusiku et al., 2010; Neugart et al., 2017; Shayanowako et al., 2021; Lugumira et al., 2025). Although these reviews provide important insights, an integrated comparison of processing effects across ALV species, bioactive compound groups, and antioxidant assays remains important. Differences in processing conditions and analytical methods must also be considered when interpreting changes in compound retention, degradation, release, and extractability. Such a synthesis can clarify variations in reported findings and inform processing recommendations for different ALVs.

Accordingly, this systematic review synthesizes and critically discusses evidence on the effects of processing methods on bioactive compounds and antioxidant activity in African leafy vegetables (ALVs). It examines how cooking, blanching, drying, and fermentation affect phenolics, flavonoids, carotenoids, chlorophyll, vitamin C, and antioxidant activity measured using DPPH, ABTS, and FRAP assays. It also explores variations in processing responses across vegetable species, compound groups, and treatment conditions, while identifying methodological limitations and research gaps. The review aims to inform household food preparation, small-scale processing,

and future research on maintaining the quality of ALVs.

Methodology

Review Design

This study adopted a systematic review design to examine the effects of processing methods on bioactive compounds and antioxidant activity in African leafy vegetables (ALVs). The review systematically identified, screened, and selected relevant published studies using predefined eligibility criteria. The design enabled a structured examination of evidence on how different processing methods influence the concentration, retention, extractability, and bioaccessibility of bioactive compounds, as well as the antioxidant activity of ALVs.

The review covered processing methods including boiling, blanching, steaming, frying, roasting, drying, fermentation, and other relevant preservation treatments. The outcomes of interest included total phenolic content, total flavonoid content, individual phenolic compounds, carotenoids, chlorophyll, vitamin C, and antioxidant activity. A systematic review design was appropriate for bringing together findings from studies investigating different vegetable species, processing conditions, and analytical outcomes, while identifying consistencies, contradictory findings, methodological limitations, and gaps in the available evidence.

Search Strategy and Information Sources

Relevant literature was identified through searches of PubMed Central, Scopus, Web of Science, and Google Scholar. The search covered publications from January 2014 to 15 March 2026. Initial searches were conducted in February 2026, and the final search was completed on 15 March 2026. Reference lists of relevant publications were also examined to identify additional eligible studies.

The search strategy combined terms relating to African leafy vegetables, processing methods, bioactive compounds, and antioxidant activity. Vegetable-related terms included "African leafy vegetables," "African indigenous vegetables," and "indigenous leafy vegetables." Terms relating to bioactive compounds included "phenolic compounds," "flavonoids," "carotenoids," "chlorophyll," "vitamin C," and "antioxidant activity." Processing-related terms included "boiling," "blanching," "steaming," "stir-frying," "roasting," "drying," "fermentation," and "microwave processing."

The scientific names of relevant vegetable species were also incorporated into the searches, including *Amaranthus* spp., *Cleome gynandra*, *Solanum* spp., *Vigna unguiculata*, *Corchorus olitorius*, *Cucurbita* spp., and *Momordica balsamina*. The search terms were combined using Boolean operators to retrieve studies examining the effects of processing on bioactive compounds and antioxidant activity in ALVs.

Eligibility Criteria

Studies were considered eligible if they investigated leafy vegetables traditionally consumed in sub-Saharan Africa, including indigenous species and other leafy vegetables widely used in African food systems; examined at least one processing or preservation method; and reported outcomes relevant to bioactive compounds or antioxidant activity. Eligible processing methods included cooking, boiling, blanching, steaming, frying, roasting, drying, fermentation, and other relevant preservation treatments.

Eligible outcomes included total phenolic content, total flavonoid content, individual phenolic compounds, carotenoids, chlorophyll, vitamin C, and antioxidant activity measured using relevant analytical assays. Publications were required to fall within the specified review period, from January 2014 to 15 March 2026, and to provide sufficient information to establish their relevance to the review objectives and extract the findings required for synthesis.

Studies were excluded if they fell outside the publication period, did not investigate relevant vegetable species or processing methods, or did not report findings related to the review outcomes. Secondary reviews were not included as primary experimental evidence, although their reference lists were examined to identify potentially eligible original studies. The classification of ALVs followed the review's operational definition, encompassing indigenous leafy vegetables and other leafy species traditionally consumed or widely used in sub-Saharan African food systems.

Study Selection Process

The study-selection process involved identification, duplicate removal, title and abstract screening, full-text assessment, and final inclusion. The database searches identified 156 records, while 14 additional records were identified through reference-list searching. Following the removal of 42 duplicate records, 128 records remained for title and abstract screening.

Two reviewers independently screened the titles and abstracts against the eligibility criteria. Records that did not meet the criteria were excluded, and the remaining full-text articles were assessed for eligibility. Forty full-text articles were assessed, of which 24 were excluded because they did not satisfy the inclusion criteria. Sixteen studies were therefore included in the final synthesis. Disagreements between reviewers were resolved through discussion, with a third reviewer consulted where necessary. The selection process is presented in Figure 1 using a PRISMA 2020 flow diagram.

Data Extraction and Organisation

Data were extracted from the included studies using a structured approach. The information collected comprised author(s), publication year, vegetable species, processing method, treatment conditions, comparator, bioactive compounds assessed, analytical methods, and principal findings.

Where available, quantitative data included measurements before and after processing, percentage changes, measurement units, sample sizes, variability estimates, and statistical significance. Processing parameters, including treatment temperature, duration, exposure to water or oil, drying conditions, fermentation conditions, and pretreatment procedures, were recorded when reported in the original publications.

Two reviewers extracted the relevant information, and a third reviewer verified the extracted data. Any discrepancies were resolved by referring to the original publications. Missing or incompletely reported information was recorded as such rather than inferred. Where multiple publications reported related experiments, their relationship was examined to avoid treating overlapping evidence as independent without justification.

The extracted data were organised into comparative tables according to vegetable species, processing method, bioactive compound category, analytical method, and reported outcome.

Critical Appraisal of Included Studies

The methodological characteristics and reporting quality of the included studies were considered when interpreting the findings. The appraisal focused on the clarity of processing protocols, suitability of raw or untreated comparators, reporting of experimental replication and statistical analyses, appropriateness of analytical methods, and completeness of quantitative results.

Particular attention was given to the distinction between measured compound concentration, compound retention, extractability, and bioaccessibility. These outcomes were considered separately because an increase in measured concentration does not necessarily indicate improved retention or greater availability for absorption. Differences in analytical procedures and reporting units were also considered when determining whether findings could be meaningfully compared.

The appraisal was used to identify methodological limitations that could affect interpretation of the evidence. However, no formal numerical risk-of-bias assessment was conducted.

Data Synthesis

The findings were synthesised systematically and organised according to processing method and outcome category. The synthesis covered phenolic compounds and flavonoids, carotenoids and vitamin C, chlorophyll and related pigments, and antioxidant activity. Evidence was compared across cooking and other thermal treatments, drying, fermentation, and additional preservation methods where relevant.

The synthesis examined the direction and consistency of reported changes, variations across vegetable species, and the influence of processing conditions. Quantitative findings were compared where the reported measurements and units were sufficiently comparable. Results

from different analytical procedures or incompatible units were not assumed to be directly equivalent.

Antioxidant activity measured using DPPH, ABTS, and FRAP assays was interpreted according to the characteristics of each assay. Conflicting findings were examined in relation to differences in vegetable species, maturity, processing conditions, analytical procedures, and comparator treatments. Potential explanations, including leaching, thermal degradation, enzyme inactivation, and the release of bound compounds, were discussed only where supported by the cited evidence.

The synthesis also considered the distribution of studies across processing methods and outcome categories to identify areas where evidence was limited or inconsistent. The findings were used to identify methodological weaknesses, establish priorities for further research, and inform context-specific recommendations for processing ALVs.

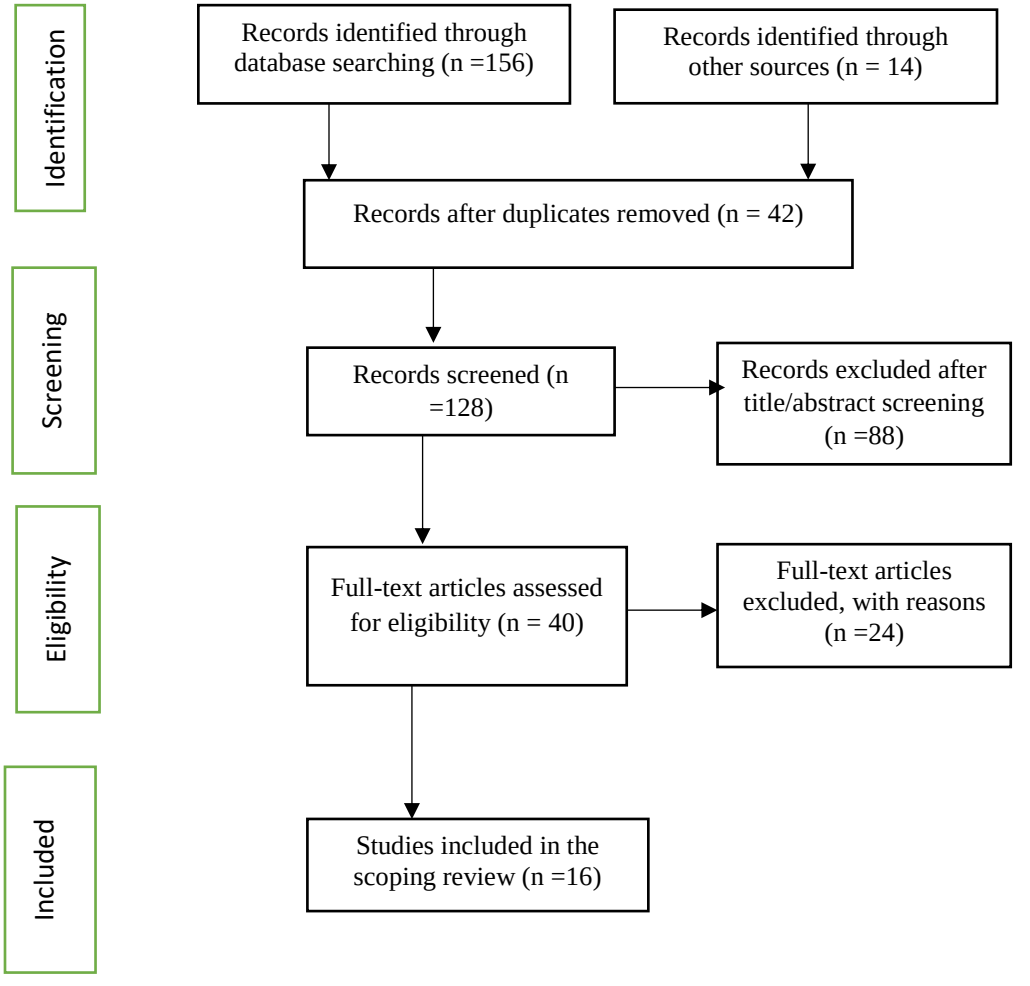


Figure 1: PRISMA flow diagram

Results and Discussion

Overview of the Included Evidence

Sixteen studies met the inclusion criteria and were synthesised. These studies investigated approximately 23 leafy vegetable species consumed in sub-Saharan Africa, including *Amaranthus* spp., African nightshade (*Solanum* spp., including *S. scabrum*, *S. nigrum*, *S. macrocarpon*, and *S. retroflexum*), spider plant (*Cleome gynandra*), jute mallow (*Corchorus olitorius*), cowpea (*Vigna unguiculata*), pumpkin leaves (*Cucurbita moschata* and *Momordica balsamina*), Chinese cabbage (*Brassica rapa* subsp. *chinensis*), *Basella alba*, *Colocasia esculenta*, *Talinum triangulare*, *Urtica dioica*, *Telfairia occidentalis*, *Vernonia fastigiata*, *Cucumis africanus*, *Adansonia digitata*, *Ceiba pentandra*, and *Hibiscus sabdariffa*.

The distribution of studies varied across processing methods. Thermal cooking methods, including boiling, steaming, stir-frying, and microwaving, were examined in six studies, while blanching, drying, fermentation, and roasting were investigated in four, five, three, and two studies, respectively. As some studies evaluated multiple processing methods and outcomes, these categories were not mutually exclusive. The distribution reflects the available evidence rather than a deliberate emphasis within the review. However, the limited number of studies on certain methods, particularly ultraviolet treatment and microwave processing, restricts the extent to which their effects can be evaluated.

The outcomes assessed also varied across studies. Total phenolic content (TPC) was the most frequently reported measure, appearing in ten studies, followed by total flavonoid content (TFC) in six. Individual phenolic compounds and carotenoids were each quantified in five studies, while vitamin C or ascorbic acid and chlorophyll were assessed in four and three studies, respectively. Antioxidant activity was evaluated in six studies, using ferric reducing antioxidant power (FRAP) in four, DPPH in three, and ABTS in three. As some studies used more than one antioxidant assay, these figures overlap. Only one study assessed α-glucosidase inhibition, a functional outcome distinct from antioxidant activity, and this is therefore considered separately. Bioaccessibility was assessed in only one study (Mashiane et al., 2021), highlighting a gap in the evidence on how processing affects the potential availability of bioactive compounds for absorption.

Across the reviewed studies, processing influenced bioactive compound content and antioxidant activity, although the direction and magnitude of these changes varied by vegetable species, processing method, treatment conditions, and outcome measured. Increases were reported in nine studies, decreases in four, mixed responses in five, and no statistically significant changes in two. Some studies reported different responses across outcomes, so these categories were not mutually exclusive. The variation highlights the importance of

considering both the characteristics of individual compounds and the processing conditions when interpreting results. Accordingly, the findings are presented by outcome category, with attention to the processing methods and conditions associated with the reported changes.

Ncube et al. (2022) found that steaming, frying, drying, and boiling all increased the TPC of *Corchorus olitorius* compared with raw leaves, with steaming producing the highest TPC and TFC. Irakoze et al. (2023b) reported marked increases in phenol and flavonoid contents following lactic acid fermentation of African black nightshade and spider plant ($p < 0.05$), with the highest phenol content reaching 228.8 mg/g GAE. Etu et al. (2024) similarly reported increases in TPC and TFC following fermentation and sautéing of *Telfairia occidentalis* and *Solanum macrocarpon*.

These consistent increases across different vegetables and thermal treatments suggest that certain processing methods can enhance the measured extractability of phenolic compounds. Three physicochemical mechanisms may explain this phenomenon, and they may operate simultaneously. First, matrix disruption occurs when heat softens plant tissues and disrupts cell walls. Plant cell walls contain cellulose, hemicellulose, pectin, and in some tissues lignin, and hydroxycinnamic acid derivatives such as chlorogenic acid, caffeoylmalic acid, and coumaroyl isocitrate are often bound to these structural components. Thermal and mechanical disruption can liberate these bound compounds, increasing their extractability during analysis (Arfaoui, 2021; Palermo et al., 2014). This mechanism is consistent with the identification of chlorogenic, neochlorogenic, and cryptochlorogenic acids as biomarkers distinguishing steam-blanched from raw Chinese cabbage (Managa et al., 2019) and with the increase in coumaroyl isocitrate reported by Mashitoa et al. (2021) following steam blanching of *Cucurbita moschata*.

Second, enzyme inactivation may prevent the oxidative degradation of phenolic compounds. Polyphenol oxidase (PPO) and peroxidase (POD) catalyse the oxidation of phenolic substrates during tissue disruption and extraction. Rapid thermal inactivation of these enzymes during the initial stages of steaming, blanching, or stir-frying can preserve phenolic compounds that would otherwise be degraded in raw samples during extraction (Arfaoui, 2021; Palermo et al., 2014). This may partly explain why processed samples sometimes contain higher measured phenolic content than raw samples, even though the absolute amount of phenolic compounds in the plant tissue has not increased.

Third, Maillard reaction products (MRPs) may form during high-temperature, low-moisture treatments such as roasting and stir-frying. These products can contribute to measured antioxidant activity through their reducing and radical-scavenging properties, potentially increasing FRAP and ABTS values even

when native antioxidants decline (Narra et al., 2024). Thus, MRP formation during roasting at 180–200 °C may partly explain the increased antioxidant activity reported by Acho et al. (2014) and Oulai et al. (2016), alongside higher polyphenol content. However, these mechanisms were not directly assessed in most reviewed studies and remain plausible explanations rather than confirmed causes. Furthermore, increased phenolic concentrations after roasting or drying may partly reflect moisture loss rather than improved compound retention.

Studies examining individual phenolic compounds provide further evidence that processing effects depend on the specific metabolites assessed. Managa et al. (2020b) reported that stir-frying increased kaempferol-3-O-rutinoside, chlorogenic acid, caffeoylmalic acid, and quercetin-3-O-xylosyl-rutinoside in African nightshade, with steaming also producing favourable results. In Chinese cabbage, sinapoyl malate was identified as a biomarker distinguishing stir-frying from other cooking techniques, while caffeoylmalic acid served this role in nightshade. Mashiane et al. (2022) found that stir-frying produced the highest concentrations of several phenolic compounds in *Momordica balsamina* compared with boiling, steaming, and microwaving. These findings extend the observations based on TPC by showing that processing can influence not only the total amount of phenolic compounds detected but also the composition and relative abundance of individual metabolites.

In contrast, five studies reported mixed or variable effects, and blanching was associated with more variable outcomes than dry thermal methods. Managa et al. (2019) found that blanching conditions influenced the retention of chlorogenic, neochlorogenic, and cryptochlorogenic acids in Chinese cabbage, with steam blanching in plain water effectively retaining selected phenolic compounds. Mashitoa et al. (2021) reported differences in individual phenolic compounds following blanching of *Cucurbita moschata*, although steam blanching in plain water retained selected compounds effectively among the treatments investigated. Managa et al. (2020a) reported that steam blanching with 5% lemon juice produced the highest chlorophyll content and overall acceptance in African nightshade, while steam blanching in water reduced tannins, oxalates, and phytates. These findings contrast with the consistent increases in measured phenolic content reported following roasting and stir-frying, illustrating that processing does not produce uniform effects across vegetables and compounds.

Differences in thermal exposure, water contact, compound stability, and leaching into processing water may explain some of this variation.

Table 1: Effects of processing methods on bioactive compounds in African leafy vegetables

Study	Vegetable(s)	Processing method(s)	Main findings on bioactive compounds
Acho et al. (2014)	*Basella alba, Colocasia esculenta, Corchorus olitorius, Solanum melongena, Talinum triangulare*	Oven-roasting at 180–200°C for 2, 4, and 6 minutes	Roasting caused a significant increase (1.12 to 26.57%) of polyphenols contents, coupled with increasing of antioxidant activity of the ALVs, while there was a decrease in carotenoid and vitamin C contents in the studied leafy vegetables
Cheptoo et al. (2019)	*Amaranthus dubius, Solanum scabrum, Urtica dioica*	Blanching, slicing, solar drying, and freeze-drying; vegetables assessed at different maturity stages	β-carotene, vitamin C, phenolic compounds, and flavonoids varied with vegetable species, maturity, and processing treatment. Freeze-drying retained more vitamin C in some treatment combinations.
Etu et al. (2024)	Telfairia occidentalis, Solanum macrocarpon	Fermentation and sautéing	Total phenolic and flavonoid contents increased. Vitamin E was higher in fermented samples than in controls, while differences in vitamin A were not statistically significant.
Irakoze et al. (2023a)	African black nightshade (*Solanum nigrum*) and African spider plant (*Cleome gynandra*)	Lactic acid fermentation using *Lactobacillus fermentum* and *Lactococcus lactis* (3% sugar + 3% salt brine)	Total ash, crude protein, and crude fibre significantly increased in starter-culture-inoculated vegetables. β-Carotene and ascorbic acid were slightly reduced. Anti-nutrients were significantly reduced in all fermented batches.
Irakoze et al. (2023b)	African black nightshade (*Solanum nigrum*) and African spider plant (*Cleome gynandra*)	Lactic acid fermentation using combined starter cultures (*Lactobacillus fermentum* and *Lactococcus lactis*)	Marked increase in phenol and flavonoid contents in all fermented vegetables ($p < 0.05$). Highest phenol content was 228.8 mg/g GAE in starter-culture-inoculated African black nightshade; flavonoid content was 10.6 mg/g QE in the same.
Managa et al. (2019)	Chinese cabbage (*Brassica rapa* L. subsp. *chinensis*)	Hot-water and steam blanching using different media	Steam blanching in plain water effectively retained selected phenolic compounds. Chlorogenic, neochlorogenic, and

			cryptochlorogenic acids were identified as biomarkers distinguishing steam treatments.
Managa et al. (2020a)	African nightshade (*Solanum retroflexum* Dun.)	Blanching (boiling, microwave, steam) with 5–20% lemon juice vs. water	Steam blanching (5% lemon juice) produced the highest chlorophyll content and overall acceptance. Steam blanching (water) reduced tannins, oxalates, and phytates. Neochlorogenic acid, chlorogenic acid, caffeoylmalic acid, kaempferol O-rhamnosyl hexoside, and rutin were identified.
Managa et al. (2020b)	African nightshade (*Solanum retroflexum*) and Chinese cabbage (*Brassica rapa* subsp. *chinensis*)	steaming, stir-frying, boiling, microwaving	Stir-frying increased kaempferol-3-O-rutinoside, chlorogenic acid, caffeoylmalic acid, and quercetin-3-O-xylosyl-rutinoside in nightshade, followed by steaming. Sinapoyl malate (Chinese cabbage) and caffeoylmalic acid (nightshade) were biomarkers distinguishing stir-frying from other cooking techniques.
Managa et al. (2020c)	Chinese cabbage (*Brassica rapa* subsp. *chinensis*) and African nightshade (*Solanum retroflexum*)	Freeze-drying, oven-drying, solar-cabinet drying, sun-drying, microwave drying	Freeze-drying retained high concentrations of ascorbic acid, chlorophyll, and several identified phenolic compounds. Sun-drying had the most negative effect on phenolic compounds in Chinese cabbage; microwave drying had the most negative effect on phenolic compounds in nightshade. Solar-cabinet drying was recommended for cost-effectiveness.
Mashiane et al. (2021)	*Momordica balsamina*	Boiling and stir-frying	Stir-frying improved the release and accessibility of β-carotene during simulated gastrointestinal digestion compared with boiling.
Mashiane et al. (2022)	*Momordica balsamina*	Boiling, steaming, microwaving, and stir-frying	Stir-frying produced the highest concentrations of several phenolic compounds. Lutein, β-carotene, and zeaxanthin increased by 60.00%, 146.15%, and 123.51%, respectively, compared with raw leaves.

Mashitoa et al. (2021; blanching study)	*Cucurbita moschata*	Hot-water and steam blanching using different media	Steam blanching in plain water retained selected phenolic compounds effectively among the blanching treatments. Coumaroyl isocitrate increased by 14.92%.
Mashitoa et al. (2021; drying study)	*Cucurbita moschata*	Freeze-drying, oven-drying, sun-drying, solar drying, and microwave drying	Freeze-drying retained high concentrations of several identified phenolic compounds and ascorbic acid. The study also reported favourable results for selected bioactivity measures.
Mncube et al. (2026)	*Cleome gynandra, Vernonia fastigiata, Amaranthus hybridus, Cucumis africanus*	Room-temperature, oven, sun, and solar drying; blanching followed by drying or freezing; freezing and post-boiling sun-drying	Sun and solar drying retained relatively high levels of phenolics, flavonoids, and proanthocyanidins in the vegetables studied. Retention varied by treatment and storage duration.
Ncube (2022)	*Corchorus olitorius*	Steaming, frying, drying methods, and boiling	All processing increased the TPC of Corchorus olitorius compared with the raw leaves. Steam-cooked samples exhibited the highest TPC, while other thermal treatments and drying methods also resulted in significant increases. TFC also increased after processing, with steaming producing the highest flavonoid content
(Oulai et al., 2016)	*Amaranthus hybridus, Andasonia digitata, Ceiba patendra, Hibiscus sabdariffa* and *Vigna unguiculata*	Roasting at 180-200°C for 2 min or more	Roasting caused a significant increase (4.77 – 32.71 %) of polyphenols contents coupled with increasing of antioxidant activity.

Table 2. Effects of processing methods on antioxidant activity in African leafy vegetables

Study	Vegetable(s)	Processing method(s)	Main findings on antioxidant activity
Acho et al. (2014)	Basella alba, Colocasia esculenta, Corchorus olitorius, Solanum melongena, Talinum triangulare	Roasting at 180–200°C	Antioxidant activity increased alongside a 1.12–26.57% increase in polyphenol content. Vitamin C and carotenoid contents decreased.
Etu et al. (2024)	Telfairia occidentalis, Solanum macrocarpon	Fermentation and sautéing	DPPH and FRAP results increased following fermentation and sautéing
Managa et al. (2020; cooking study)	African nightshade (Solanum retroflexum) and Chinese cabbage (Brassica rapa subsp. chinensis)	Boiling, steaming, stir-frying, and microwave cooking	FRAP activity was higher in all cooked samples than in raw vegetables. Steaming significantly increased FRAP activity, followed by stir-frying; microwaving produced the lowest FRAP activity among the cooking treatments. Stir-fried nightshade leaf extract showed the most effective inhibition against α-glucosidase activity (IC_{50} = 26.4 µg/mL vs. acarbose IC_{50} = 69.83 µg/mL).
Managa et al. (2020; drying study)	African nightshade (Solanum retroflexum) and Chinese cabbage (Brassica rapa subsp. chinensis)	Freeze-drying, oven-drying, solar-cabinet drying, and sun-drying	Freeze-drying retained antioxidant activity, ascorbic acid, and chlorophyll. Sun-drying had the most negative effect on phenolic compounds in Chinese cabbage; microwave drying had the most negative effect on phenolic compounds in nightshade.
Mashiane et al. (2022)	African pumpkin (Momordica balsamina) leaves	Boiling, steaming, microwaving, and stir-frying	Stir-frying increased antioxidant activity measured using DPPH and ABTS compared with raw leaves and leaves prepared using the other tested cooking methods.
Mashitoa et al. (2021; blanching study)	Pumpkin leaves (Cucurbita moschata)	Water-bath blanching and steam blanching using different media	Raw leaves had the highest overall antioxidant capacity. Among the blanching treatments, steam blanching in plain water produced the highest antioxidant capacity, with FRAP of 1.25 µmol TEAC g^{-1} fresh weight and ABTS of 1.51 µmol TEAC g^{-1} fresh weight.

Water-based treatments such as boiling and blanching can cause water-soluble phenolic compounds to leach into the cooking water, reducing the amount retained in the vegetable when the liquid is discarded. Dry thermal methods such as roasting and stir-frying avoid leaching losses but may promote thermal degradation or the formation of MRPs. The balance between release, degradation, and leaching therefore determines the net effect of processing on phenolic content.

Overall, the evidence indicates that processing outcomes for phenolic compounds and flavonoids reflect the interaction between phenolic release, enzyme inactivation, chemical degradation, and losses into processing water. No single processing method can be considered universally superior for preserving all phenolic compounds in ALVs. Instead, the effect depends on the vegetable species, the specific phenolic compound or group of compounds, and the processing conditions applied. This conclusion is consistent with Palermo et al. (2014) and Narra et al. (2024), who explained that cooking can either increase or decrease measured phytochemical content depending on processing conditions, the food matrix, and the chemical characteristics of individual compounds.

Effects of processing on phenolic compounds and flavonoids

Nine studies reported increases in measured phenolic content following thermal processing, making this the most consistent finding in the review. Acho et al. (2014) found that roasting at 180–200 °C for 2–6 minutes increased polyphenol content by 1.12–26.57% in *Basella alba*, *Colocasia esculenta*, *Corchorus olitorius*, *Solanum melongena*, and *Talinum triangulare*. Oulai et al. (2016) reported increases of 4.77–32.71% following roasting of *Amaranthus hybridus*, *Adansonia digitata*, *Ceiba pentandra*, *Hibiscus sabdariffa*, and *Vigna unguiculata*.

Effects of processing on carotenoids and vitamin C

The effects of processing on carotenoids and vitamin C were less consistent than those observed for phenolic compounds, and the two nutrient groups responded differently to processing. This section distinguishes between compound concentration, retention, and bioaccessibility, because these are related but distinct concepts.

Vitamin C retention varied according to vegetable species, maturity stage, and processing treatment. Cheptoo et al. (2019) reported differences in vitamin C retention among *Amaranthus dubius*, *Solanum scabrum*, and *Urtica dioica* across blanching, slicing, solar drying, and freeze-drying treatments, with freeze-drying retaining more vitamin C in some treatment combinations. Managa et al. (2020c) found that freeze-drying retained high concentrations of ascorbic acid in African nightshade and Chinese cabbage. Acho et al. (2014) reported decreases in vitamin C content following roasting, and Irakoze et al. (2023a) reported slight reductions in

ascorbic acid following lactic acid fermentation. Because vitamin C is sensitive to heat, oxygen, and light, thermal degradation and leaching into processing water may contribute to its loss during preparation (Kinyi et al., 2022). The extent of these losses depends on the vegetable and the conditions under which processing is performed. Water-based cooking methods such as boiling are associated with greater leaching losses than steam-based or dry methods, while freeze-drying minimises both thermal degradation and leaching.

Carotenoid responses were more variable. Acho et al. (2014) reported reductions in carotenoid content following roasting, whereas Mashiane et al. (2022) found increases in measured lutein, β-carotene, and zeaxanthin concentrations following stir-frying of *Momordica balsamina*, with increases of 60.00%, 146.15%, and 123.51%, respectively, compared with raw leaves. These contrasting results indicate that carotenoid responses depend on the vegetable, processing conditions, and individual compounds assessed. Palermo et al. (2014) similarly explained that cooking can either degrade phytochemicals or increase their extractability from plant tissues. Therefore, an increase in measured carotenoid concentration after processing should not automatically be interpreted as the formation of additional carotenoids, because changes in tissue structure and moisture content may also affect the results.

Beyond measured concentrations, processing can influence the accessibility of carotenoids during digestion. Mashiane et al. (2021) reported that stir-frying improved β-carotene release and accessibility during simulated gastrointestinal digestion compared with boiling. This finding complements the increased carotenoid concentrations reported by Mashiane et al. (2022) following stir-frying of the same vegetable. Stir-frying with oil may enhance carotenoid bioaccessibility through lipid-assisted micellarisation, because carotenoids are lipophilic and their transfer from the food matrix to mixed micelles is facilitated by dietary lipids. However, improved bioaccessibility in a laboratory digestion model does not necessarily establish increased absorption or greater health benefits in humans. True physiological effects depend on human absorption, first-pass metabolism, and colonic fermentation of unabsorbed fractions. Future research should therefore transition from in vitro digestion models to animal feeding trials or human intervention studies to establish whether processing-related changes in bioaccessibility translate into measurable health benefits.

The distinction between concentration, retention, and bioaccessibility is particularly important for carotenoids. A processing method that increases measured carotenoid concentration may do so through moisture loss, matrix disruption, or improved extractability rather than through increased retention. Similarly, a method that improves bioaccessibility in vitro may not improve retention if it also causes thermal degradation.

Processing methods should therefore be evaluated according to both compound retention and accessibility, where evidence is available.

Effects of processing on chlorophyll

Chlorophyll was assessed in three studies, making it the least-studied outcome in this review. Managa et al. (2020a) reported that steam blanching with 5% lemon juice produced the highest chlorophyll content in African nightshade, alongside the highest overall acceptance. Managa et al. (2020c) found that freeze-drying retained high concentrations of chlorophyll in African nightshade and Chinese cabbage, whereas other drying methods resulted in greater losses. These findings suggest that chlorophyll retention is favoured by treatments that minimise thermal exposure and water contact, such as steam blanching and freeze-drying. Chlorophyll contributes to the characteristic green colour of leafy vegetables and is often used as a visual indicator of quality. However, the limited number of studies assessing chlorophyll means that conclusions about the effects of processing on this compound remain tentative. Future studies should include chlorophyll as a routine outcome alongside other bioactive compounds to strengthen the evidence base.

Effects of processing on antioxidant activity

Antioxidant activity was measured in six studies, most commonly using FRAP (four studies), DPPH (three studies), and ABTS (three studies). The direction and magnitude of change depended on the treatment, the vegetable, and the assay used. This section compares findings across assays and discusses the mechanistic basis for assay-specific responses.

FRAP measures reducing capacity through a single-electron transfer (SET) mechanism at low pH. It does not measure thiol-based antioxidants or compounds that act primarily through hydrogen atom transfer (HAT), such as certain carotenoids. Managa et al. (2020b) found that FRAP activity was higher in all cooked samples of African nightshade and Chinese cabbage than in raw vegetables, with steaming producing the highest FRAP activity, followed by stir-frying, and microwaving producing the lowest. Etu et al. (2024) reported increased FRAP following fermentation and sautéing of *Telfairia occidentalis* and *Solanum macrocarpon*. Mashitoa et al. (2021) found that raw pumpkin leaves had the highest overall antioxidant capacity, although steam blanching in plain water produced the highest FRAP among the blanching treatments (1.25 µmol TEAC g^{-1} fresh weight).

DPPH operates primarily through SET and HAT mechanisms and is sterically hindered by large molecules. Etu et al. (2024) reported increased DPPH following fermentation and sautéing. Mashiane et al. (2022) found that stir-frying increased DPPH in *Momordica balsamina* compared with raw leaves and other cooking methods.

ABTS works in both aqueous and organic phases and can detect

both hydrophilic and lipophilic antioxidants. Mashiane et al. (2022) reported increased ABTS following stir-frying of *Momordica balsamina*. Mashitoa et al. (2021) reported ABTS of 1.51 µmol TEAC g^{-1} fresh weight for steam-blanched pumpkin leaves.

The contrasting findings across assays are partly explained by differences in their mechanisms. FRAP is purely a SET assay and does not measure HAT-active compounds such as carotenoids. DPPH is sterically hindered and may underestimate the activity of large phenolic molecules. ABTS is less sterically hindered and works in both aqueous and organic phases, making it more sensitive to lipophilic antioxidants. Consequently, results obtained using these assays are not directly interchangeable and may produce different responses to changes in phytochemical composition. An increase in FRAP does not necessarily correspond to an increase in DPPH or ABTS, and an increase in one assay does not establish that all antioxidant properties have improved.

A major chemical paradox in the thermal processing of vegetables is that total antioxidant activity often increases even when specific heat-sensitive vitamins such as vitamin C or individual carotenoids degrade. Three mechanisms may explain this phenomenon. First, as discussed in Section 3.2, Maillard reaction products formed during roasting and stir-frying possess strong reducing power and can inflate FRAP and ABTS measurements. Second, enzyme inactivation during rapid thermal treatment can prevent the enzymatic degradation of phenolics, making them appear higher in processed samples than in raw samples where endogenous enzymes actively degrade them during extraction. Third, matrix disruption can liberate bound hydroxycinnamic acid derivatives from cell-wall lignin and pectin complexes, increasing their extractability and their contribution to measured antioxidant activity. These mechanisms may operate simultaneously, and their relative contributions depend on the processing method and conditions.

It is also important to distinguish antioxidant activity from specific biological effects. Managa et al. (2020b) reported that stir-fried nightshade leaf extract showed effective inhibition against α-glucosidase activity (IC_{50} = 26.4 µg/mL vs. acarbose IC_{50} = 69.83 µg/mL). This is a distinct functional endpoint that measures enzyme inhibition, not radical-scavenging or reducing capacity. α-Glucosidase inhibition is relevant to postprandial glucose management but is not equivalent to antioxidant activity and should not be interpreted as evidence that the vegetable has greater antioxidant capacity. Enzyme-inhibition results are therefore reported separately from the principal antioxidant analysis.

Finally, statistically significant laboratory results should be distinguished from nutritionally meaningful effects. An increase in antioxidant activity measured using one laboratory assay does not establish that the processed vegetable provides greater health benefits in humans. In vitro antioxidant assays are useful for comparing processing

methods under controlled conditions, but they cannot predict physiological effects. Future research should therefore interpret antioxidant results alongside other outcomes, including compound retention, bioaccessibility, and where possible, biological endpoints measured in animal or human studies.

Effects of fermentation and drying

Fermentation produced favourable changes in selected phytochemical measures in the reviewed studies. Irakoze et al. (2023a) reported that total ash, crude protein, and crude fibre significantly increased in starter-culture-inoculated African black nightshade and spider plant, while β-carotene and ascorbic acid were slightly reduced and antinutrients were significantly reduced in all fermented batches. Irakoze et al. (2023b) reported marked increases in phenol and flavonoid contents following lactic acid fermentation using combined starter cultures of *Lactobacillus fermentum* and *Lactococcus lactis* ($p < 0.05$), with the highest phenol content reaching 228.8 mg/g GAE. Etu et al. (2024) reported increases in TPC and TFC following fermentation and sautéing of *Telfairia occidentalis* and *Solanum macrocarpon*, with vitamin E higher in fermented samples than in controls, while differences in vitamin A were not statistically significant.

These findings agree in showing that fermentation can modify the phytochemical composition of ALVs. Changes following fermentation may be associated with microbial activity and the transformation or release of compounds within plant tissues. Lactic acid bacteria can produce enzymes that hydrolyse bound phenolic compounds, releasing aglycones that may be more readily extracted and absorbed. However, the extent to which microbial transformation explains the reported increases, as opposed to the release of existing compounds, would require further investigation under controlled conditions. Future studies comparing similar vegetables, fermentation cultures, and processing durations could help establish which conditions are most effective for retaining or improving specific bioactive compounds and antioxidant activity.

Drying methods produced contrasting outcomes depending on the vegetable and the compounds assessed. Managa et al. (2020c) found that freeze-drying retained high concentrations of ascorbic acid, chlorophyll, and selected phenolic compounds in African nightshade and Chinese cabbage. Sun-drying had the most negative effect on phenolic compounds in Chinese cabbage, while microwave drying had the most negative effect in nightshade. Mncube et al. (2026) reported that sun and solar drying retained relatively high levels of phenolics, flavonoids, and proanthocyanidins in *Cleome gynandra*, *Vernonia fastigiata*, *Amaranthus hybridus*, and *Cucumis africanus*, although retention varied by treatment and storage duration.

These findings demonstrate that the effectiveness of drying depends on both the vegetable

species and the compounds being assessed. Freeze-drying performed favourably for selected outcomes, but it should not be presented as universally superior. Its equipment requirements and cost may limit its accessibility for household and small-scale applications. Managa et al. (2020c) identified solar-cabinet drying as a cost-effective option in the context of their study. This finding highlights the importance of considering practical feasibility alongside compound retention when recommending preservation methods. The most appropriate drying method should balance the retention of targeted bioactive compounds, processing costs, available equipment, microbial safety, storage stability, and the intended use of the vegetables.

Conclusions

This review demonstrates that processing methods influence the bioactive compounds and antioxidant activity of African leafy vegetables in ways that are compound-specific, species-specific, and method-dependent. The principal contribution of this review is the integrated synthesis of evidence across vegetable species, processing methods, and analytical outcomes, which shows that no single processing method is universally optimal for preserving all bioactive compounds and antioxidant properties of ALVs.

The most consistent finding was that thermal treatments such as steaming, stir-frying, and roasting increased measured phenolic content in selected vegetables, likely through a combination of cell-wall disruption, enzyme inactivation, and the formation of Maillard reaction products. Fermentation also produced favourable changes in phenolic and flavonoid contents in some cases. Freeze-drying retained selected bioactive compounds, including ascorbic acid and chlorophyll, whereas other drying and cooking treatments resulted in variable retention or losses of specific compounds. Antioxidant activity varied according to the vegetable, processing method, and analytical assay used, and the three main assays (DPPH, ABTS, and FRAP) were not directly interchangeable.

However, several findings remain uncertain. The effects of processing on carotenoids and vitamin C were less consistent than those on phenolic compounds, and the evidence base for chlorophyll, bioaccessibility, and enzyme inhibition was limited to one or two studies. The imbalance in the number of studies across processing methods means that conclusions for less-studied methods remain tentative. These uncertainties reflect both the inherent variability of the food matrix and the methodological limitations of the available studies, including inconsistent reporting units, limited use of individual compound quantification, and the rarity of bioaccessibility and human-relevant endpoints.

Processing practices should therefore be selected according to the desired nutritional outcomes, the characteristics of the vegetable, and the feasibility of application at household and small-scale levels. The most important research priority is the

adoption of standardised processing conditions, consistent analytical methods, and comparable reporting units across studies, alongside the inclusion of multiple outcomes within the same experiment and the extension of bio-accessibility research to animal and human studies. Such evidence would support more reliable, context-specific processing recommendations for improving the utilisation and preservation of African leafy vegetables.

Limitations

Several limitations of the original studies constrained the synthesis. Comparisons across studies were limited by differences in vegetable species, processing conditions, analytical methods, and reporting units. Many studies reported TPC rather than individual phenolic metabolites, limiting the ability to determine which specific compounds were affected. Only one study assessed bioaccessibility rather than concentration alone, and only one reported enzyme-inhibition activity. Increases in measured concentrations may reflect changes in moisture content, compound extractability, or chemical transformation rather than increases in the total amount of a compound. Differences in antioxidant assays also limit direct comparisons between studies.

The review was limited by the absence of a formal risk-of-bias assessment, variation in study methods, and the databases, search terms, publication period, and full-text availability. Uneven study numbers across processing methods, particularly ultraviolet treatment and microwave processing, also limited the strength of some conclusions.

Recommendations

Policy Recommendations

National agricultural extension services and public health authorities in sub-Saharan Africa should update community nutrition guidelines to incorporate optimized cooking and processing methods. Training programs should emphasize methods that minimize nutrient leaching, such as discouraging prolonged boiling in excessive water volumes.

Government and non-governmental interventions aimed at food security and rural enterprise should support the adoption of affordable processing infrastructure such as indirect solar dryers and community-scale steam blanchers to reduce post-harvest losses while preserving bioactive quality.

Food regulatory authorities and standards bodies should establish clear processing standards and nutritional quality benchmarks for commercialized ALV products (e.g., dried vegetable powders and fermented preserves) entering formal markets.

Practical Recommendations

For daily household preparation, short-duration steaming or stir-frying should be prioritized over prolonged boiling to enhance the extractability and retention of phenolic compounds and flavonoids, particularly in species such as nightshade (*Solanum* spp.) and amaranth (*Amaranthus* spp.).

When boiling is preferred for taste or cultural reasons, minimal water volumes should be used, or the remaining cooking liquid should be retained and consumed in soups or stews to capture leached water-soluble vitamins (such as vitamin C) and soluble phenolics.

Small-scale processors and smallholders should transition from direct open-sun drying to indirect solar drying or shade drying to minimize photochemical and thermal degradation of delicate carotenoids and ascorbic acid. Where capital investment permits, freeze-drying remains the benchmark for premium ALV powders.

Recommendations for Future Research

Future research should standardise processing conditions, analytical methods, and reporting units while assessing multiple nutritional outcomes within the same experiments. Studies should also distinguish compound retention from extractability and bioaccessibility and, where feasible, investigate effects beyond in vitro assays. Processing recommendations should balance nutritional quality, functional properties, cost, and practicality. For example, steaming or stir-frying may benefit phenolic retention in nightshade, whereas freeze-drying or minimal-water methods may better preserve vitamin C, although cost and equipment requirements must be considered.

Future research should use standardised processing conditions, clearly reported analytical methods, and consistent reporting units to improve comparisons across vegetable species and studies. Investigations should also assess multiple nutritional outcomes within the same experiment, including phenolic compounds, carotenoids, vitamin C, and antioxidant activity.

Where feasible, studies should distinguish compound retention from extractability and bioaccessibility, and should extend beyond in vitro models to animal feeding trials or human intervention studies. Such evidence would support more reliable processing recommendations that balance nutritional quality, functional properties, and practical feasibility for households and small-scale vegetable processors. For instance, for nightshade, steaming or stir-frying may be preferable if phenolics are the priority; for vitamin C retention, freeze-drying or minimal-water methods may be better, although their cost and equipment requirements must be considered.

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