CHAPTER 13

Kale as a functional vegetable. Nutritional value, bioactive compounds and the influence of processing and cultivation

Olesia Priss
Yanina Chetverikova
Viktoriia Vertegel

Abstract

Kale (*Brassica oleracea* var. *acephala*) is one of the most valuable leafy green vegetables due to its high content of important phytonutrients.

Recently, kale has attracted increasing attention from scientists as a functional product for health nutrition.

This study summarizes current knowledge about the chemical composition of kale, focusing on glucosinolates, isothiocyanates, and phenolic compounds that exert antioxidant, anti-inflammatory, and chemoprotective effects.

Particular attention is paid to the influence of biotic and controlled abiotic stresses on the accumulation of these compounds in plant tissues.

The work also examines the influence of culinary and industrial processing technologies on the preservation and transformation of biologically active substances in kale. It is summarized that heat treatment using water significantly reduces the content of glucosinolates and phenols, while steaming, short-term frying, and freezing after blanching preserve these compounds better.

Innovative non-thermal technologies, such as high hydrostatic pressure, also show potential to increase the conversion of glucosinolates to biologically active isothiocyanates.

The results highlight the importance of optimized growing and processing conditions to stabilize the nutritional and functional value of kale products. Therefore, kale can be considered a promising raw material for the development of functional health products for the prevention of diet-related chronic diseases.

Keywords

Kale, glucosinolates, isothiocyanates, phenolic compounds, cultivation, processing, nutritional quality, functional food.

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13.1 Introduction

The global trend toward a transition to healthy eating and a healthy lifestyle is gaining significant momentum. Against this background, there is a growing interest among researchers in dietary patterns as a key to combating non-communicable diseases. Expanding the diversity of plant-based products in the daily diet is an important factor in providing the human body with essential vitamins, microelements, amino acids, and other biologically active compounds that support normal physiological functions. On the other hand, the transition to diets with a predominance of plant-based components is considered an important direction in the context of sustainable food systems, as it contributes to reducing environmental pressure, rational use of resources, and improving food accessibility. At the same time, an increasing number of studies focus on expanding the range of plant crops in human diets. It is believed that out of approximately 300,000 plant species, only about 5,000 have ever been used as food, and only 150–200 have been widely used in modern diets [1]. Most of the remaining species are still underutilized and belong to the group of so-called underutilized, neglected, traditional, rare, or wild vegetables. Despite this, they have high nutritional value, are rich in biologically active compounds, and are often characterized by ecological plasticity. Therefore, according to many researchers, they should be "brought back to the plate" through promotion, domestication, and commercialization [2].

Ukraine has significant potential for underutilized, niche vegetable crops – both introduced and local – which occupy very small cultivation areas but are distinguished by their nutritional value, ornamental appeal, and market prospects. In the forest-steppe zone, atypical species have already been tested, including anguria cucumber (*Cucumis anguria*), kiwano (*Cucumis metuliferus*), okra (*Abelmoschus esculentus*), aromatic cephalophora (*Cephalophora aromatica*), lemongrass (*Cymbopogon citratus*), and chufa or tiger nut (*Cyperus esculentus*). These plants combine nutritional and spicy-aromatic value with pronounced decorative qualities, which allows them to be used both in urban landscaping and as elements of "edible landscapes" in parks and household plots [3].

Expanding the range of cultivated crops can become a key way to diversify agricultural production in times of military threats, climate change, and price fluctuations. At the same time, demand for new, niche, and leafy vegetables is growing by 30% annually [4]. This creates a reserve for increasing dietary diversity among Ukrainians, especially with regard to leafy greens, where actual consumption is 9% below the recommended dietary level [5]. Global studies and reviews show that underutilized, nutrient-rich vegetables and legumes (including traditional varieties) help combat "hidden hunger", increase the resilience of agrosystems to drought and extreme weather, and provide small farmers with new sources of income [6, 7].

Kale (*Brassica oleracea var. acephala*) is an underutilized niche crop with exceptional nutritional and functional value, making it ideal for expanding the vegetable assortment in Ukraine. It is rich in vitamins A, C, K, minerals (calcium, iron, magnesium, potassium), dietary fiber, glucosinolates, polyphenols, carotenoids, and flavonoids, and is therefore classified among superfoods with antioxidant, anti-inflammatory, hypolipidemic, and potentially anticancer effects [8]. Studies on organically grown kale show that a 100 g serving can significantly cover the daily requirements for calcium, manganese, iron, phosphorus, and copper, and provide 5.7–8.7 g of prebiotic carbohydrates, combining mineral richness with the function of a "food for the microbiome" [9, 10]. This makes kale a promising tool for combating micronutrient deficiencies and obesity, especially in diets with low consumption of leafy vegetables.

For niche production, it is important that kale is quite adaptable to growing conditions: it can produce high biomass in open fields and greenhouses, is suitable for organic systems, vertical farming, and hydroponics; optimization of nutrition allows regulation of yield and the content of bioactive compounds. Varieties differ in morphology, productivity, and nutrient composition. European and Asian studies confirm this, providing a basis for breeding adapted forms with better keeping quality and phytonutrients. With the growing demand for organic and highly nutritious green vegetables, kale can become a competitive niche crop for small and medium-sized farms, urban and vertical farming, provided that technologies are adapted to Ukrainian conditions, local varieties are created and a consumer culture of its consumption is formed.

Many publications position kale as a superfood with antioxidant, anti-inflammatory, anticancer and antibacterial properties [10]. Kale is widely used in culinary applications. It is consumed raw in salads and "green" smoothies, added to soups, stews, stews, omelets, pan-fried dishes, used as a side dish or vegetable base, and also baked and dried in the form of "chips" as a healthy snack. In processing, kale is used for the production of frozen and canned vegetable mixes, juices and functional drinks, including fermented juices, where under the influence of lactic acid bacteria the content of polyphenols and antioxidant activity increases, while the content of antinutritional compounds decreases [11]. Leaf powder or puree is added to bread, baked goods, snacks, beverages, and soups as a functional ingredient that increases the content of dietary fiber, minerals, and bioactive compounds [12]. Kale is actively used in the development of functional products for the prevention of chronic diseases (cardiovascular, metabolic, inflammatory), in particular in experiments with fermented juice and soups intended for the elderly [13]. In addition to food applications, kale is used to create biodegradable edible films and coatings in combination with sodium alginate, which contributes to environmentally friendly food packaging [14].

The aim of the work was to summarize current scientific data on the nutritional value and bioactive compounds of kale (*Brassica oleracea* var. *acephala*), as well as to analyze the influence of cultivation conditions, abiotic stresses and processing technologies on the accumulation and preservation of glucosinolates, isothiocyanates and phenolic compounds that determine its functional properties.

13.2 Glucosinolates and the dependence of their sweetness and content on abiotic and biotic factors

Kale is characterized by a high content of biologically active compounds – vitamins (A, C, K), minerals, polyphenols, carotenoids, chlorophylls, fiber and, above all, glucosinolates (GLS), which determine the significant antioxidant, anti-inflammatory and anticarcinogenic activity of this crop. GLS are sulfur- and nitrogen-containing thioglucosides with a single basic skeleton derived from amino acids. GLS are classified into aliphatic, indole, and aromatic groups. A wide range of total GLS content has been described for kale (2.25–93.9 μmol/g dry weight), with the ratio of indole to aliphatic compounds varying significantly depending on the variety, plant tissue, developmental stage, growing conditions and analytical method. In most edible kale varieties, sinigrin, glucoiberin and glucobrassicin dominate, often with notable contributions from progoitrin and neoglucobrassicin. Together, they can provide 70–95% of the total glucosinolates in the leaf. **Table 13.1** summarizes the approximate range of the most common individual glucosinolates in kale.

Table 13.1 Content of major glucosinolates in kale leaves

GLS class	Common GLS in kale leaves	Range, μmol/g dry wt.	Contribution to total GLS, %
Aliphatic	sinigrin	0.29–9.66	26.6
	glucoiberin	2.38–25.07	36.5
	progoitrin	0.09–2.52	3.5
	gluconapin	0.00–0.86	1.1
	glucoraphanin	0.00–1.27	1.7
Indole	glucobrassicin	0.32–17.92	24.3
	neoglucobrassicin	0.00–3.39	4.5
Aromatic	gluconasturtiin	0.00–1.38	1.8

Source: compiled by the authors based on [15–19]

In plant tissues, GLS are chemically stable. However, when cells are disrupted, the substrate is hydrolyzed by endogenous myrosinase to form isothiocyanates (ITCs), nitriles, and thiocyanates, which play a key role in plant defense against pathogens and herbivores and mediate chemopreventive effects in humans. N. Baenas reported that in kale leaves, glucoraphanin is the dominant GLS (≈ 12 mg/100 g fresh weight), and the corresponding ITC, iberin, is the main individual ITC (≈ 0.8 mg/100 g) [16]. Recent studies clearly emphasize that the preventive effects of cruciferous vegetables – anticancer, anti-inflammatory, and antioxidant – are primarily associated not with GLS themselves but with their hydrolysis products, mainly ITCs. It has been shown that ITCs, rather than GLS, are the direct chemopreventive agents that regulate tumor initiation, growth, and development in various organs [20].

Phylogenetically and morphologically distinct kale groups (German, American, Italian forms, sabellica-type variants, etc.) exhibit considerable genotypic variability in their GLS profiles: the content of individual compounds and the total GLS level in 25 cultivars vary widely, with differences between genotypes often exceeding the influence of environmental conditions [21]. Analysis of organic kale genotypes showed that even among seven samples, the content of sulfur-containing metabolites, GLS breakdown products, and associated polyphenols and carotenoids varied substantially [22]. For 30 genotypes grown in different regions, a broad range in GLS, phenolic compounds, and flavonoid content was observed; certain genotypes combined elevated GLS levels with high antioxidant activity, indicating the potential for targeted breeding for nutraceutical traits [23].

Seasonality combines changes in temperature, day length, and light intensity, so its effect on GLS in kale cannot be separated from climatic factors. In a broad set of *Brassica oleracea* forms (including kale), higher total GLS concentrations in leaves were observed in spring than in autumn; statistical analysis showed that total and indole GLS levels were explained by a combination of mean temperature, photosynthetically active radiation, and day length 2–4 weeks before harvest. Similar seasonal patterns have been observed in Chinese kale. In most cultivars, GLS content, phenolic compounds, and antioxidant activity were higher in spring and autumn than in winter, which is attributed to a more favorable combination of temperature and light and reduced stress from short days and cold [24].

Temperature acts as a moderate stressor, capable of both stimulating and suppressing GLS accumulation. In field trials, total GLS content in *Brassica oleracea* showed a negative linear but positive quadratic relationship with mean temperature two weeks before harvest. Moderate increases in temperature led to higher concentrations, whereas very low or very high temperatures caused degradation. In a "plant factory" for kale, the optimal growth temperature was 20–23°C, whereas the maximum GLS content occurred at 14–17°C; further increases in temperature reduced their levels [25]. During cold acclimation, some cultivars (curly, lacinato) exhibited a sharp increase in aliphatic GLS (e.g., glucoraphanin > 200%), whereas in the "wild" type, cold mainly decreased glucobrassicin [26].

Light affects kale both through the daily light integral and through spectral composition and photoperiod. In a field trial with kale, cabbage, and broccoli, total leaf GLS content was positively correlated with PPF two weeks before harvest; however, at excessively high values, the curve became quadratic, indicating saturation and photostress. In artificial-light growth chambers for kale, it was shown that, under the same daily light integral, the highest GLS content occurred under a 14-hour photoperiod at moderate intensity (~ 200 μmol m^{-2} s^{-1}), whereas very long (22 h) or short (10 h) days reduced their levels [27].

Phenological stage modulates the response to seasonal and climatic factors. In the field, GLS content in kale leaves increases from the seedling stage to the onset of flowering. At the consumer stage, indole and aromatic GLS (primarily glucobrassicin) reach their maximum, whereas during the transition to the generative phase, aliphatic forms are translocated to flower buds, where, especially for sinigrin, the highest concentrations are recorded. Spring plantings reach the "consumer" stage under longer days and moderately higher temperatures, which is usually associated with higher total GLS content, whereas autumn plantings approach flowering under shorter days and lower temperatures. In sprouts, microgreens, and baby leaves under spring-summer conditions, aliphatic GLS content is generally much higher than in mature plants, but sensitivity to temperature and light at these early stages is also more pronounced.

In summary, seasonality, through the combination of temperature, day length, and light intensity, determines the "age and stage" of the plant at which the GLS profile in kale is formed. Moderately cool conditions with sufficient light and a moderate photoperiod (14–16 h) during the phase of active leaf growth favor maximal total GLS content, particularly indole GLS, whereas extreme cold or heat, excessively short or long days, and full flowering most often lead to reduced total content or a shift of the profile toward aliphatic forms.

Agronomic practices can be deliberately used as a "stress tool" to increase phenolic compounds, carotenoids, and GLS in kale, but excessive stress reduces yield and quality. Abiotic stresses (soil salinity, drought, temperature, solar radiation, phytohormones) are increasingly considered as managed technologies for bioactive compound enrichment. Controlled abiotic stresses activate signaling pathways and transcription of secondary metabolism genes, resulting in increased enzyme activity, enhanced synthesis of phenolics and GLS, and their accumulation in tissues. In kale, such controlled stresses (particularly cold and radiation) have been shown to substantially increase the content of protective metabolites with anti-inflammatory and anticancer properties [28]. At the same time, excessive stress increases the risk of up to 50% yield loss, accumulation of antinutritional compounds (oxalates, nitrates, phytates, tannins), and deterioration of consumer quality.

The type of fertilizer and overall agronomic management shape the kale microbiota and associated risks. In South Korean farms, traditional organic fertilizers based on manure were associated with a high proportion of coliform bacteria carrying antibiotic resistance genes compared with other fertilization systems. The potential for horizontal transfer of these genes within the coliform population has been confirmed [29]. Therefore, fertilizer practices should be reconsidered as a component of food-chain biosafety.

13.3 Effect of processing technologies on glucosinolates and isothiocyanates

Thermal culinary methods differently affect GLS retention and ITCs formation. Boiling kale in water causes cell structure disruption, diffusion and leaching of GLS into the cooking water, as well as thermal degradation and rapid inactivation of myrosinase, resulting in retention of only about 20–40% of the original GLS and ITCs content in the vegetable. In contrast, steaming and stir-frying involve minimal water contact and moderate heating time, allowing at least 50% of GLS and their corresponding ITCs to be preserved in kale. Studies on the *Brassica* family consistently identify steaming as the most favorable method for preserving these compounds, whereas boiling and blanching in a large volume of water are considered the most destructive [15].

Industrial pretreatment and preservation methods also have a critical impact on GLS content in kale. Studies of fresh, blanched, boiled, frozen, canned, and dried kale leaves showed that after blanching followed by rapid freezing, total GLS content remained the highest among all storage methods even after 12 months, whereas canned samples exhibited the lowest values [30]. Frozen products from blanched material contained on average 20% more GLS than those frozen after boiling, 58% more than canned products, and nearly 50% more than dried samples. Data summarized across various vegetables indicate that the combination of "blanching-rapid freezing" is optimal for preserving both GLS and the potential amount of ITCs during subsequent consumption.

Physical processing methods, particularly high hydrostatic pressure, are considered a promising tool for managing the myrosinase–glucosinolate system without significant deterioration of sensory qualities. For kale leaves, treatment at 600 MPa resulted in a substantial increase in myrosinase activity and the highest conversion rate of GLS to ITCs, reaching 70.4%, although the total GLS content in these samples was lower than in raw or solely thermally treated leaves [31]. Microscopic analysis revealed characteristic damage to veins, edges, and leaf surfaces, which facilitates enzyme-substrate contact and enhances ITCs formation. A review of modern non-thermal methods (high pressure, pulsed electric fields, ultraviolet irradiation) for various cruciferous vegetables generally confirms that these techniques can either increase or modify the profile of GLS and their hydrolysis products depending on processing conditions, while remaining gentler compared with conventional thermal pasteurization.

The mechanism of ITCs formation from GLS in kale is determined by a combination of factors, some of which are directly related to processing. The activity of endogenous myrosinase, which catalyzes GLS hydrolysis, is significantly reduced by intense heating, particularly during prolonged boiling or sterilization, which decreases ITCs yield in favor of nitriles and other by-products. Individual studies on various *Brassica* species have shown that changes in the pH of the reaction medium to household acidic or slightly alkaline values, as well as dilution during chopping or preparation, can sharply increase the proportion of ITCs among hydrolysis products.

A combined analysis of the data allows the formulation of a kale-processing approach aimed at maximizing GLS retention and stimulating ITCs formation. At the household level, short steaming or brief stir-frying is recommended, possibly with prior leaf chopping to activate myrosinase. In industrial settings, the most rational approach is blanching followed by rapid freezing or gentle drying, preferably via lyophilization, which ensures the highest residual GLS content after long-term storage. A promising direction is the application of high hydrostatic pressure as an alternative to thermal pasteurization for producing functional kale ingredients with increased ITCs content. Considering the pH of the medium, degree of leaf chopping, and hydrolysis conditions when making beverages, purees, and other processed kale products offers additional opportunities to deliberately increase the bioavailability of these compounds in final food systems.

13.4 Phenolic compounds

Phenolic compounds in kale form one of the key components of its antioxidant and functional potential. Approximately three dozen phenolic components have been identified in kale, mainly flavonol glycosides of quercetin and kaempferol, as well as derivatives of hydroxycinnamic acids – p-coumaric, ferulic, sinapic, and caffeic acids.

Total flavonol content in fresh leaf tissue is about 646 mg rutin equivalents (RE)/100 g, and hydroxycinnamic acids are about 204 mg RE/100 g, totaling roughly 0.85 g phenolic compounds per 100 g fresh weight (FW). The main individual compounds are highly glycosylated acylated derivatives of kaempferol and quercetin, accounting for approximately 18–19% and 16–17% of total flavonols, respectively. After acid hydrolysis, two aglycones predominate – quercetin (~ 44 mg/100 g) and kaempferol (~ 58 mg/100 g) – indicating the dominance of their glycosides in the phenolic profile [32].

Studies of phenolic acid content in kale leaves have identified nine acids, with ferulic and caffeic acids being the main ones (totaling 4269 and 4887 ng/g FW, respectively) [33]. A significant portion of these acids occurs in bound form, contributing to cell wall protection and plant stress responses. In the red-leafed kale variety "Redbor F1", an even more diverse polyphenolic spectrum has been described –47 different glycosides of flavonols, anthocyanins, and hydroxycinnamic acids, with a total content of approximately 872 mg polyphenolic equivalents per 100 g fresh weight. Under field conditions, this hybrid exhibits about 20% higher soluble phenolics and flavonoids compared with the green cultivar Dwarf Blue Scotch, which correlates with higher antioxidant activity.

Studies of different genotypes confirm that most secondary metabolites in kale are phenolic compounds: 70–80% of identified metabolites belong to flavonoids (kaempferol and quercetin glycosides, anthocyanins), chlorogenic and other hydroxycinnamic acids, and coumarins [34]. In kale microgreens and sprouts, a wide spectrum of polyphenols is also detected, including numerous flavonoids (such as anthocyanins) and hydroxycinnamic acids, with their profile and bioavailability strongly depending on developmental stage and cultivation conditions [35].

Overall, the kale phenolic complex correlates closely with antioxidant activity, and variations by cultivar, genotype, and agronomic conditions result in a wide range of phenolic content, which is important to consider when assessing the nutritional and functional value of the raw material.

13.5 Effect of processing technologies on the phenolic compounds

Phenolic compounds in kale are highly sensitive to processing methods. Most studies show that heating in contact with water reduces total phenolic content due to oxidation and leaching: even short boiling or blanching can substantially decrease total polyphenols in kale [36]. In kale, boiling in water caused the greatest degradation and leaching of polyphenols, whereas steaming resulted in the smallest losses, with water blanching falling in between. In another study, thermal treatments (blanching, freezing, subsequent "boil-in-bag") in green and red curly kale cultivars led to a significant reduction in total phenolics and antioxidant activity, with the red cultivar retaining phenolic compounds better [37].

At the same time, there are contrasting findings: when kale was prepared at home using short-term steaming, an increase in phenolic content (~ +86% compared with raw samples) and a simultaneous rise in antioxidant activity were observed, attributed to the softening of the cell matrix and release of bound polyphenols. For different plant parts (leaf, stem, whole plant), steaming has been shown to provide the best extraction of phenolics compared with other thermal regimes, if extraction is performed in water [38]. A comparison of steaming and sous-vide processing for the kale cultivar cv. Crispa confirmed that both methods statistically reduced total phenolic content, but losses depended on the plant part; fresh kale leaves exhibited one of the highest phenolic levels (~ 159 mg/100 g) among the organs studied [39].

A review of modern traditional and innovative cooking methods highlights that boiling and vacuum cooking in water promote phenolic losses through leaching, whereas methods with minimal water contact (steaming, microwaving, sous-vide in vacuum bags) more often preserve or even increase the extractable amount of phenolic compounds due to cell wall disruption [40].

Extrusion cooking of snacks with added fresh kale showed that high-temperature, short-time extrusion does not degrade phenolic compounds; instead, their content and antioxidant activity clearly increase with higher proportions of kale in the formulation [41]. Optimal parameters (30% fresh kale, 36% moisture) ensured maximal phenolic acid content (primarily sinapic acid) and high antioxidant activity. Similar results were obtained for corn-based snacks with 2–8% kale addition: phenolic acid content and antioxidant potential increased with the proportion of kale, and extrusion did not reduce polyphenolic activity.

In the production of frozen and canned kale, it was shown that freezing after blanching provides significantly higher residual polyphenol content after one year of storage (≈ 83–171 mg/100 g) compared with canning, where polyphenol levels were lower (≈ 91–94 mg/100 g) [42]. Reviews of kale as a functional ingredient emphasize that freezing and mild drying methods better preserve the polyphenolic profile, whereas canning with prolonged sterilization leads to substantial reductions in phenolic compound content [40].

13.6 Advantages and challenges of kale cultivation

In addition to all its health-related dietary benefits, kale is distinguished by its simple agronomic requirements. This plant tolerates adverse conditions such as high salinity, drought, and extreme temperatures allowing harvests nearly year-round in diverse climates. Kale provides multiple cuttings: older leaves can be harvested to stimulate new growth, ensuring a high total yield per area.

However, kale yield and nutritional value vary greatly depending on cultivar, cultivation system, fertilization, light, and microclimate. Conditions that maximize leaf biomass often slightly reduce the concentration of beneficial phytochemicals, and vice versa. Significant differences in yield and content of phenolics, flavonoids, anthocyanins, and carbohydrates are observed among cultivars and local populations [43].

Kale grows well on deep, moderately acidic to neutral soils (pH ~ 6–7.5) with high organic matter and uniform moisture. Proper selection of sowing dates allows maximization of yield and economic return without significant quality losses [44]. Fertilization systems and biostimulatory stresses (salinity, temperature) can enhance phenolic, carotenoid, and GLS content, thereby strengthening the health-promoting properties of the produce.

Kale responds well to organic fertilizers (compost, black soldier fly larvae frass), which increase yield and dry matter content while simultaneously reducing pest populations compared with mineral fertilizers [45]. High yields and enhanced vitamin C and other bioactive compound content can be achieved in both soil-based and soilless systems (hydroponics, aquaponics, vertical "multi-layer" beds) compared with conventional soil cultivation. In temperate climates, protective structures (high and low tunnels with mulching) allow successful winter cultivation of kale [46].

In open fields and greenhouses, kale produces the greatest biomass due to high natural light and lower planting density; in growth chambers, biomass is lower, though leaves are thinner (high leaf area per gram) [47]. Organomineral fertilizers provide the highest productivity for curly kale compared with purely organic or unfertilized systems.

Despite its hardiness, kale is highly susceptible to diseases and pests, particularly in intensive and protected systems. In soilless greenhouses, significant losses (> 70%) have been reported due to stem rots caused by the fungus Agroathelia delphinii; the risk is increased by non-sterilized organic substrates (rice straw, coconut husk, etc.). Organic production makes it more difficult to control diseases and extend post-harvest life; organic kale generally has a shorter shelf life, increasing food losses.

In open fields, clubroot (*Plasmodiophora brassicae*) is a major concern: on acidic, waterlogged soils with high Al^{3+} content and with prolonged monoculture, the disease spreads extensively, reducing yield and impairing plant nutrition. In urban cultivation, powdery mildew and black rot often dominate; warm and humid conditions, high planting density, and intensive cultivation exacerbate their impact, while straw mulching has variable effects on these diseases [48].

Among pests, aphids, cabbage whitefly, and other insects reduce yield, quality, and glucosinolate content in leaves. Minimizing losses requires integrated protection systems, cultural practices (crop rotation, timing, soil-cover materials), biocontrol, and rigorous sanitation of equipment and planting material.

13.7 Conclusion

Kale is considered a truly promising leafy green vegetable crop with high nutritional and functional value. It is distinguished by a rich complex of biologically active compounds, particularly GLS, ITCs, and phenolic substances. These components determine the pronounced antioxidant, anti-inflammatory, antibacterial, and potential anticancer properties of this crop, which underlines its important role in the formation of a healthy diet.

It has been established that the accumulation of bioactive compounds in kale tissues largely depends on the genotype, environmental growing conditions, and the influence of abiotic factors. The application of controlled stress factors and the improvement of agronomic practices make it possible to regulate the level of secondary metabolites, thereby creating opportunities to enhance the biological value of the final products.

An important factor in preserving the functional properties of kale is the selection of appropriate culinary and technological processing methods. It has been demonstrated that intensive thermal treatment in large volumes of water leads to degradation of 60–80% of glucosinolates and phenolic compounds.

At the same time, steaming, short-term stir-frying, and the use of modern processing technologies contribute to the maximum retention of nutrients. Therefore, the integrated optimization of cultivation conditions and processing regimes can become a strategic approach to stabilizing bioactive compounds in kale as a raw material for the production of functional foods.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper.

Data availability

Manuscript has no associated data.

Use of artificial intelligence statement

The authors used the AI assistant Perplexity (Grok 4.1, Perplexity AI) for translation and literature source selection. The authors bear full responsibility for the final manuscript. Generative AI tools are not credited and are not responsible for the final results.

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Authors' contributions

Olesia Priss: Supervision, Conceptualization, Methodology, Writing – original draft, Project administration.

Yanina Chetverikova: Writing – original draft, Writing – review and editing, Investigation.

Viktoriia Vertegel: Writing – original draft, Investigation, Formal analysis, Validation.

References

1. Hunter, D., Borelli, T., Beltrame, D. M. O., Oliveira, C. N. S., Coradin, L., Wasike, V. W. et al. (2019). The potential of neglected and underutilized species for improving diets and nutrition. Planta, 250 (3), 709–729. https://doi.org/10.1007/s00425-019-03169-4
2. Knez, M., Ranić, M., Gurinović, M. (2023). Underutilized plants increase biodiversity, improve food and nutrition security, reduce malnutrition, and enhance human health and well-being. Let's put them back on the plate! Nutrition Reviews, 82 (8), 1111–1124. https://doi.org/10.1093/nutrit/nuad103

3. Hapon, S., Felbaba-Klushina, L., Hapon, Y. (2023). Poorly common vegetables and spicy-aromatic plants and their use in landscaping. Biology & ecology, 9 (1), 8–15. https://doi.org/10.33989/2023.9.1.290165
4. Shchetyna, S. (2023). Assessment of vegetable crop cultivation in open ground conditions in Ukraine. Balanced Nature Using, 3, 144–152. https://doi.org/10.33730/2310-4678.3.2023.287829
5. Kvasha, S., Andrei, P., Mancini, M. C., Vakulenko, V. (2024). Food security in Ukraine today's conditions. International Journal of Food Sciences and Nutrition, 75 (6), 622–636. https://doi.org/10.1080/09637486.2024.2379825
6. Talucder, M. S. A., Ruba, U. B., Robi, Md. A. S. (2024). Potentiality of Neglected and Underutilized Species (NUS) as a future resilient food: A systematic review. Journal of Agriculture and Food Research, 16, 101116. https://doi.org/10.1016/j.jafr.2024.101116
7. Priss, O., Korchynskyy, I., Kryvko, Y., Korchynska, O. (2023). Leveraging Horseradish's Bioactive Substances for Sustainable Agricultural Development. International Journal of Sustainable Development and Planning, 18 (8), 2563–2570. https://doi.org/10.18280/ijsdp.180828
8. Łukaszyk, A., Kwiecień, I., Kanik, A., Blicharska, E., Tatarczak-Michalewska, M., Białowąs, W. et al. (2025). Nutritional, Therapeutic, and Functional Food Perspectives of Kale (Brassica oleracea var. acephala): An Integrative Review. Molecules, 30 (21), 4214. https://doi.org/10.3390/molecules30214214
9. Thavarajah, D., Siva, N., Johnson, N., McGee, R., Thavarajah, P. (2019). Effect of cover crops on the yield and nutrient concentration of organic kale (Brassica oleracea L. var. acephala). Scientific Reports, 9 (1). https://doi.org/10.1038/s41598-019-46847-9
10. Cârlea, I., Tarkanyi, P., Lăcătuș, M., Bordean, D.-M., Rădulescu, L. (2025). Kale, a complementary, rich mineral food – a review. Journal of Agroalimentary Processes and Technologies, 2024 (30) (4), 497–502. https://doi.org/10.59463/japt.2024.2.53
11. Subedi, U., Raychaudhuri, S., Fan, S., Ogedengbe, O., Obanda, D. N. (2024). Fermenting kale (Brassica oleracea L.) enhances its functional food properties by increasing accessibility of key phytochemicals and reducing antinutritional factors. Food Science & Nutrition, 12 (8), 5480–5496. https://doi.org/10.1002/fsn3.4195
12. Khalid, W., Iqra, Afzal, F., Rahim, M. A., Abdul Rehman, A., Faiz ul Rasul, H., Arshad, M. S. et al. (2023). Industrial applications of kale (Brassica oleracea var. sabellica) as a functional ingredient: a review. International Journal of Food Properties, 26 (1), 489–501. https://doi.org/10.1080/10942912.2023.2168011

13. Duarte, C., Pinheiro, R., Mata, F., Pinto, E., Fernandes, Â., Vaz-Velho, M. (2025). Innovative fortified kale soup formulation designed for the elderly. International Journal of Gastronomy and Food Science, 41, 101216. https://doi.org/10.1016/j.ijgfs.2025.101216
14. De Oliveira, E., Bonfim, K., Aouada, F., Azeredo, H., Moura, M (2023). A sustainable approach on the potential use of kale puree in edible wraps. Applied Food Research, 3 (1), 100261. https://doi.org/10.1016/j.afres.2022.100261
15. Sikorska-Zimny, K., Beneduce, L. (2020). The glucosinolates and their bioactive derivatives in Brassica: a review on classification, biosynthesis and content in plant tissues, fate during and after processing, effect on the human organism and interaction with the gut microbiota. Critical Reviews in Food Science and Nutrition, 61 (15), 2544–2571. https://doi.org/10.1080/10408398.2020.1780193
16. Baenas, N., Marhuenda, J., García-Viguera, C., Zafrilla, P., Moreno, D. (2019). Influence of Cooking Methods on Glucosinolates and Isothiocyanates Content in Novel Cruciferous Foods. Foods, 8 (7), 257. https://doi.org/10.3390/foods8070257
17. Cartea, M. E., Velasco, P., Obregón, S., Padilla, G., de Haro, A. (2008). Seasonal variation in glucosinolate content in Brassica oleracea crops grown in northwestern Spain. Phytochemistry, 69 (2), 403–410. https://doi.org/10.1016/j.phytochem.2007.08.014
18. Sotelo, T., Velasco, P., Soengas, P., Rodríguez, V. M., Cartea, M. E. (2016). Modification of Leaf Glucosinolate Contents in Brassica oleracea by Divergent Selection and Effect on Expression of Genes Controlling Glucosinolate Pathway. Frontiers in Plant Science, 7. https://doi.org/10.3389/fpls.2016.01012
19. Lee, H.-H., Yang, S.-C., Lee, M.-K., Ryu, D.-K., Park, S., Chung, S.-O. et al. (2015). Effect of Developmental Stages on Glucosinolate Contents in Kale (Brassica oleracea var. acephala). Horticultural Science and Technology, 33 (2), 177–185. https://doi.org/10.7235/hort.2015.14017
20. Soundararajan, P., Kim, J. S. (2018). Anti-Carcinogenic Glucosinolates in Cruciferous Vegetables and Their Antagonistic Effects on Prevention of Cancers. Molecules, 23 (11), 2983. https://doi.org/10.3390/molecules23112983
21. Hahn, C., Müller, A., Kuhnert, N., Albach, D. (2016). Diversity of Kale (Brassica oleracea var. sabellica): Glucosinolate Content and Phylogenetic Relationships. Journal of Agricultural and Food Chemistry, 64 (16), 3215–3225. https://doi.org/10.1021/acs.jafc.6b01000
22. Bianchi, G., Picchi, V., Tava, A., Doria, F., Walley, P. G., Dever, L. et al. (2024). Insights into the phytochemical composition of selected genotypes of organic

kale (Brassica oleracea L. var. acephala). Journal of Food Composition and Analysis, 125, 105721. https://doi.org/10.1016/j.jfca.2023.105721

23. Shafi, S., Mukherjee, G., Murtaza, I. (2022). Chemo profiling and antioxidant activity of different genotypes of Brassica oleracea var acephala grown across Kashmir in different environments. International Journal of Health Sciences, 4862–4877. https://doi.org/10.53730/ijhs.v6ns3.6983
24. Wang, Y., Miao, H., Zhang, F., Sun, B., Wang, Q. (2025). Seasonal Variation in Nutritional Substances in Varieties of Leafy Chinese Kale (Brassica oleracea var. alboglabra): A Pilot Trial. Agronomy, 15 (3), 671. https://doi.org/10.3390/agronomy15030671
25. Chowdhury, M., Kiraga, S., Islam, M. N., Ali, M., Reza, M. N., Lee, W.-H. et al. (2021). Effects of Temperature, Relative Humidity, and Carbon Dioxide Concentration on Growth and Glucosinolate Content of Kale Grown in a Plant Factory. Foods, 10 (7), 1524. https://doi.org/10.3390/foods10071524
26. Hahn, C., Müller, A., Kuhnert, N., Albach, D. C. (2023). A Cold Case – Glucosinolate Levels in Kale Cultivars Are Differently Influenced by Cold Temperatures. Horticulturae, 9 (9), 953. https://doi.org/10.3390/horticulturae9090953
27. Kim, S., Bok, G., Shin, J., Park, J. (2022). Effects of Photoperiod and Light Intensity on the Growth and Glucosinolates Content of Three Brassicaceae Species in a Plant Factory. Journal of Bio-Environment Control, 31 (4), 416–422. https://doi.org/10.12791/ksbec.2022.31.4.416
28. Ortega-Hernández, E., Antunes-Ricardo, M., Jacobo-Velázquez, D. A. (2021). Improving the Health-Benefits of Kales (Brassica oleracea L. var. acephala DC) through the Application of Controlled Abiotic Stresses: A Review. Plants, 10 (12), 2629. https://doi.org/10.3390/plants10122629
29. Yum, S. J., Yu, S. Y., Kim, S. M., Jeong, H. G. (2025). Antibiotic Resistance Genes and Microbiota in Brassica oleracea var. acephala Cultivated in South Korea: Potential for Resistance Transmission. Journal of Agricultural and Food Chemistry, 73 (3), 2156–2166. https://doi.org/10.1021/acs.jafc.4c11161
30. Korus, A., Słupski, J., Gębczyński, P., Banaś, A. (2014). Effect of preliminary processing and method of preservation on the content of glucosinolates in kale (Brassica oleracea L. var. acephala) leaves. LWT – Food Science and Technology, 59 (2), 1003–1008. https://doi.org/10.1016/j.lwt.2014.06.030
31. Wu, Y.-H., Lin, Y.-H., Wang, C.-Y. (2022). High hydrostatic pressure treatment induced microstructure changes and isothiocyanates biosynthesis in kale. Food Chemistry, 383, 132423. https://doi.org/10.1016/j.foodchem.2022.132423
32. Olsen, H., Aaby, K., Borge, G. I. A. (2009). Characterization and Quantification of Flavonoids and Hydroxycinnamic Acids in Curly Kale (Brassica oleracea L. Convar.

acephala Var. sabellica) by HPLC-DAD-ESI-MSn. Journal of Agricultural and Food Chemistry, 57 (7), 2816–2825. https://doi.org/10.1021/jf803693t

33. Olsen, H., Aaby, K., Borge, G. I. A. (2010). Characterization, Quantification, and Yearly Variation of the Naturally Occurring Polyphenols in a Common Red Variety of Curly Kale (Brassica oleracea L. convar. acephala var. sabellica cv. 'Redbor'). Journal of Agricultural and Food Chemistry, 58 (21), 11346–11354. https://doi.org/10.1021/jf102131g
34. Tomas, M., Zhang, L., Zengin, G., Rocchetti, G., Capanoglu, E., Lucini, L. (2021). Metabolomic insight into the profile, in vitro bioaccessibility and bioactive properties of polyphenols and glucosinolates from four Brassicaceae microgreens. Food Research International, 140, 110039. https://doi.org/10.1016/j.foodres.2020.110039
35. Liu, Z., Shi, J., Wan, J., Pham, Q., Zhang, Z., Sun, J. et al. (2021). Profiling of Polyphenols and Glucosinolates in Kale and Broccoli Microgreens Grown under Chamber and Windowsill Conditions by Ultrahigh-Performance Liquid Chromatography High-Resolution Mass Spectrometry. ACS Food Science & Technology, 2 (1), 101–113. https://doi.org/10.1021/acsfoodscitech.1c00355
36. Krzemińska, J., Kapusta-Duch, J., Smoleń, S., Kowalska, I., Słupski, J., Skoczeń-Słupska, R. et al. (2024). Iodine enriched kale (Brassica oleracea var. sabellica L.) – The influence of heat treatments on its iodine content, basic composition and antioxidative properties. PLOS ONE, 19 (6), e0304005. https://doi.org/10.1371/journal.pone.0304005
37. Olsen, H., Grimmer, S., Aaby, K., Saha, S., Borge, G. I. A. (2012). Antiproliferative Effects of Fresh and Thermal Processed Green and Red Cultivars of Curly Kale (Brassica oleracea L. convar. acephala var. sabellica). Journal of Agricultural and Food Chemistry, 60 (30), 7375–7383. https://doi.org/10.1021/jf300875f
38. Da Silva, A. S. L., Benevides, C. M. de J., Da Silva, H. B. M., Silva, M. V. L., Montes, S. de S., Souza, A. C. S. et al. (2023). Multivariate Analysis of the content of bioative compounds in kale (Brassica oleracea). Peer Review, 5 (13), 254–270. https://doi.org/10.53660/612.prw1709
39. Lafarga, T., Viñas, I., Bobo, G., Simó, J., Aguiló-Aguayo, I. (2018). Effect of steaming and sous vide processing on the total phenolic content, vitamin C and antioxidant potential of the genus Brassica. Innovative Food Science & Emerging Technologies, 47, 412–420. https://doi.org/10.1016/j.ifset.2018.04.008
40. Khalid, W., Ikram, A., Nadeem, M. T., Arshad, M. S., Rodrigues, S. O., Pagnossa J. P. et al. (2023). Effects of Traditional and Novel Cooking Processes on the Nutritional and Bioactive Profile of Brassica oleracea (Kale). Journal of Food Processing and Preservation, 2023, 1–12. https://doi.org/10.1155/2023/2827547

41. Soja, J., Combrzyński, M., Oniszczuk, T., Biernacka, B., Wójtowicz, A., Kupryaniuk, K. et al. (2023). The Effect of Fresh Kale (Brassica oleracea var. sabellica) Addition and Processing Conditions on Selected Biological, Physical, and Chemical Properties of Extruded Snack Pellets. Molecules, 28 (4), 1835. https://doi.org/10.3390/molecules28041835
42. Korus, A., Lisiewska, Z. (2011). Effect of preliminary processing and method of preservation on the content of selected antioxidative compounds in kale (Brassica oleracea L. var. acephala) leaves. Food Chemistry, 129 (1), 149–154. https://doi.org/10.1016/j.foodchem.2011.04.048
43. Thavarajah, D., Lawrence, T., Powers, S., Jones, B., Johnson, N., Kay, J. et al. (2021). Genetic variation in the prebiotic carbohydrate and mineral composition of kale (Brassica oleracea L. var. acephala) adapted to an organic cropping system. Journal of Food Composition and Analysis, 96, 103718. https://doi.org/10.1016/j.jfca.2020.103718
44. Patel, P., Ganvit, S., Patel, N., Ahir, M. P., Rathod, H. (2025). Impact of Varying Planting Dates on Agronomic Performance and Quality of Kale Under South Gujarat's Sub-Humid Climatic Conditions. Journal of Advances in Biology & Biotechnology, 28 (9), 614–625. https://doi.org/10.9734/jabb/2025/v28i92911
45. Abiya, A. A., Kupesa, D. M., Beesigamukama, D., Kassie, M., Mureithi, D., Thairu, D. et al. (2022). Agronomic Performance of Kale (Brassica oleracea) and Swiss Chard (Beta vulgaris) Grown on Soil Amended with Black Soldier Fly Frass Fertilizer under Wonder Multistorey Gardening System. Agronomy, 12 (9), 2211. https://doi.org/10.3390/agronomy12092211
46. Daryadar, M., Mairapetyan, K. H., Tovmasyan, A. H., Aleksanyan, J. S., Tadevosyan, A. H., Kalachyan, L. H. et al. (2019). Productivity of Leafy Green Vegetable Kale in Soilless Cultivation Conditions. Journal of Agricultural Science and Food Research, 10 (2). https://doi.org/10.35248/2593-9173.19.10.260
47. Bincader, S., Pongpisutta, R., Tiansawang, T., Khienman, S., Boonyaritthongchai, P., Phuntumart, V. et al. (2025). Brassica oleracea var. sabellica: A New Host of Agroathelia delphinii in Soilless Cultivation Systems in Central Thailand. Horticulturae, 11 (4), 411. https://doi.org/10.3390/horticulturae11040411
48. Silva, K. E., Correa, E. B., Silva, E. A., Pereira, W. E., Silva, J. C. P., Medeiros, F. H. V. (2022). Urban production of kale (Brassica oleracea var. acephala) in Brazil: survey of diseases and factors that contribute to their outbreak. Summa Phytopathologica, 48 (1), 17–24. https://doi.org/10.1590/0100-5405/194018