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Research Article

Comparative analysis of physicochemical properties and antioxidant activities of kale (*Brassica oleracea* var. *acephala*) under organic and conventional cultivation systems

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Abstract This study evaluated the physicochemical properties, bioactive compounds, and antioxidant activities of kale cultivated under conventional and organic systems. Moisture content showed little difference between groups, while ash values varied more widely in organic kale. Crude protein was higher in organic kale, averaging about 0.55% compared to 0.39% in conventional samples, and crude fat was also slightly greater at up to 2.36% in organic kale versus 2.07% in conventional kale. Total polyphenol and flavonoid contents were greater in organic kale, reaching over 312.53 μg GAE/g and 75.40 μg QE/g, while the lowest values in conventional kale were around 238.56 μg GAE/g and 18.07 μg QE/g. The highest β-carotene concentration was observed in organic kale at more than 31.02 μg/g, exceeding the lowest level in conventional kale of about 20.71 μg/g. Glucosinolate analysis revealed increased levels in organic samples, particularly gluconapin and 4-methoxyglucobrassicin. Antioxidant assays demonstrated that organic kale exhibited superior activity, with DPPH radical scavenging close to 62.01-64.59%, ABTS scavenging above 75.00%, and reducing power values approaching 0.85-0.95. These findings indicate that organic cultivation enhances the accumulation of bioactive compounds and improves antioxidant capacity, supporting the nutritional and functional advantages of organically grown kale.

Keywords Kale, organic, conventional, glucosinolates, antioxidant activity

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1. Introduction

Kale (*Brassica oleracea* var. *acephala*), a cruciferous leafy vegetable, has recently received increasing attention as a functional food due to its high content of bioactive compounds and associated health benefits (Fahey, 2003). Recognized as one of Time magazine's "Top 10 superfoods," kale has become a representative health-promoting ingredient, widely utilized in diverse culinary applications and popularized through the media and social networks (Satheesh and Fanta, 2020). Nutritionally, kale is rich in micronutrients such as lutein, β-carotene, vitamin C, calcium, and iron, as well as bioactive compounds including polyphenols, flavonoids, and sulforaphane, which are known to exhibit antioxidant, anti-inflammatory, and anticancer activities (Kim et al., 2017; Ortega-Hernandez et al., 2021). In particular, polyphenols and flavonoids contribute to the scavenging of reactive oxygen species, thereby playing a preventive role against cardiovascular diseases, aging, and cancer, while β-carotene, as a provitamin A compound, supports skin protection and visual health (Chen and Zhang, 2021; Ma et al., 2025; Russo et al., 2017).

With the growing recognition of its functional and nutritional value, consumer demand for kale has shifted from basic dietary consumption toward organically cultivated products that align with health and environmental sustainability. However, kale was ranked third on the Environmental Working Group's "Dirty Dozen" list in 2020, indicating a high potential for pesticide residues and underscoring the need for careful consumer awareness (EWG, 2020). Moreover, cruciferous vegetables, including kale, are known to be highly responsive to environmental stresses, which can influence the metabolic pathways involved in the biosynthesis of phenolic compounds and carotenoids (Samec et al., 2022). Considering that kale is frequently consumed raw or as fresh juice, such compositional variations induced by cultivation practices and environmental factors may directly affect its nutritional and physiological properties.

The content of bioactive compounds in agricultural products is strongly influenced not only by genetic factors but also by cultivation practices, soil properties, climate, harvest timing, and post-harvest processing (Kim et al., 2021). Organic cultivation, which excludes chemical fertilizers and synthetic pesticides while relying on natural pest control measures and organic fertilizers, often exposes plants to greater environmental stress (Oliveira et al., 2013). Such stress can promote the biosynthesis of secondary metabolites, including polyphenols and vitamin C, thereby increasing the accumulation of bioactive compounds (Faller and Fialho, 2010). Indeed, several studies have reported that organically cultivated fruits and vegetables exhibit higher polyphenol content and antioxidant activity compared with conventionally grown produce (Faller and Fialho, 2010; Oliveira et al., 2013). However, conflicting findings have also been documented, with some studies reporting no significant differences or even superior results for conventional crops (Hunter et al., 2011; Lee et al., 2015). These discrepancies are likely attributable to multiple factors, including crop cultivar, regional conditions, organic certification standards, and cultivation or harvest practices, thereby underscoring the need for crop-specific comparative studies.

In this study, three organic and three conventionally cultivated kale samples were analyzed for proximate composition, bioactive compound contents, and antioxidant activities. The objective was to identify statistically significant differences between the two cultivation systems and to provide scientific evidence for the functional superiority of organically grown kale. The findings are expected to serve as a fundamental resource for the development of eco-friendly, high-functional vegetables and to provide practical information for consumer decision-making.

2. Materials and methods

2.1. Materials and chemicals

Three conventionally cultivated kale and three organically cultivated kale, produced in different regions, were purchased through online markets and used for analysis. The samples were labeled according to the cultivation method as follows: (A), (B), and (C) represent conventionally cultivated kale, while (D), (E), and (F) represent organically cultivated kale. Folin-Ciocalteu reagent, catechin, gallic acid, and potassium persulfate for the quantification of total polyphenols and flavonoids were obtained from Sigma-Aldrich (St. Louis, MO, USA). Reagents used for proximate analysis and antioxidant activity assays, including DPPH (2,2-diphenyl-1-picrylhydrazyl), ABTS [2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)], and those for reducing power, were purchased from Sigma-Aldrich or Junsei Chemical Co., Ltd. (Tokyo, Japan). For the quantification of β-carotene and glucosinolates, appropriate standards and solvents for high-performance liquid chromatography (HPLC) were also purchased from the same suppliers.

2.2. Sample pretreatment

Kale samples were washed thoroughly under running water to remove debris, and residual surface moisture was removed. Edible parts were cut into small pieces, homogenized, and either used fresh or subjected to freeze- drying. For each replicate, 100 g of kale sample was used to prepare the homogenized material. For freeze-drying, samples were rapidly frozen at -75°C in an ultra-low freezer (DF-810, Ilshin Lab Co., Seoul, Korea), followed by lyophilization (IlShin Biobase, Dongduchun, Korea). The dried samples were ground into fine powder using a grinder (Hanil, Seoul, Korea) and passed through 30- and 100-mesh sieves to obtain uniform particle size. The final powders were stored in plastic tubes at -20°C until further analysis.

2.3. Proximate composition analysis

Proximate composition was analyzed following AOAC (1995) standard procedures. Moisture content was determined

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by oven-drying samples at 105℃ (EYELA, Tokyo, Japan) until a constant weight was achieved. Crude protein was determined using the semi-Kjeldahl method with an automatic nitrogen analyzer (Kjeltec 2400 AUT, Foss Tecator, Eden Prairie, MN, USA), applying a conversion factor of 6.25. Crude fat was measured using a Soxhlet apparatus (Soxtec System HT 1043, Foss Tecator, Eden Prairie, MN, USA) with diethyl ether as the extraction solvent. Ash content was quantified by direct ashing at 550℃ in a muffle furnace (SH-FU-11MGE, Samheung Scientific, Sejong, Korea).

2.4. Preparation of extracts and determination of antioxidant compounds

Freeze-dried kale powder (10 g) was mixed with 50 mL of 70% ethanol for 3 min and extracted at room temperature for 30 min using an ultrasonic bath. The extract was centrifuged at 13,500 ×*g* for 15 min to separate the supernatant and precipitate. The supernatant was filtered through Whatman No. 1 filter paper, diluted to an appropriate concentration, and used for the determination of total polyphenol and total flavonoid contents.

Total polyphenol content was determined using a modified Folin-Denis method (Singleton and Rossi, 1965). One gram of sample powder was suspended in 4 mL distilled water, sonicated at 40℃ for 5 min, and centrifuged at 3,000 rpm for 10 min. An aliquot (0.5 mL) of the supernatant was mixed with 0.5 mL Folin reagent, incubated for 3 min at room temperature, followed by the addition of 1.5 mL of 2% Na_2CO_3. The mixture was incubated for 2 h in the dark, and absorbance was measured at 760 nm using a microplate reader (Infinite M200 Pro, Tecan Group Ltd., San Jose, CA, USA). Results were expressed as gallic acid equivalents (GAE) per gram of sample.

Total flavonoid content was analyzed following the method of Woisky and Salatino (1998). After sample extraction, 1 mL of the supernatant was mixed with 1 mL of 2% $AlCl_3$ methanolic solution and incubated for 15 min at room temperature. Absorbance was measured at 430 nm, and the results were expressed as quercetin equivalents (QE) per gram of sample.

The β-carotene content of kale was determined following the method of Hwang et al. (2012). Freeze-dried kale powder (1 g) was extracted three times with 3 mL of ethyl acetate containing 100 mg/L butylated hydroxytoluene (BHT), followed by centrifugation at 3,000 ×*g* for 5 min. The combined supernatants were evaporated under reduced pressure, and the residue was dissolved in 250 μL diethyl ether and 750 μL of mobile phase (methanol:acetonitrile:tetrahydrofuran, 50:45:5, v/v/v). After filtration through a PVDF membrane (0.48 μm), the solution was analyzed by HPLC (Shimadzu, Japan) using a C_{18} Novapak column (3.9×150 mm, 5 μm) at 25℃, with a flow rate of 1 mL/min. Detection was performed at 480 nm using a programmable multi-wavelength detector.

2.5. HPLC analysis of glucosinolates

Glucosinolate content was quantified according to the ISO protocol (1992). Freeze-dried kale powder (50 mg) was extracted with 70% ethanol at 70℃ for 5 min, followed by centrifugation at 20,000 ×*g* for 10 min at 4℃. The residue was re-extracted under the same conditions, and the supernatants were combined. Extracts were purified using Bio-Rad Mini Bio-Spin columns (cross-linked dextran gel G-25, Bio-Rad Laboratories, Hercules, CA, USA), preconditioned with 20 mM sodium acetate buffer (pH 5.5). Purified extracts were incubated with Helix pomatia-derived aryl sulfatase (75 μL, Type H-1) for 24 h at room temperature to achieve desulfation, after which desulfo-glucosinolates were eluted with 1.5 mL distilled water, filtered (0.2 μm), and analyzed by HPLC.

Glucosinolate separation was performed on an Agilent 1200 HPLC system equipped with a PDA detector (229 nm) and a Waters Symmetry 300 C_{18} column (75 mm×4.6 mm, 3.5 μm). The column was maintained at 40℃, with a flow rate of 0.5 mL/min and injection volume of 20 μL. The mobile phase consisted of solvent A (water) and solvent B (acetonitrile) with a gradient elution from 0-35% B over 35 min, followed by re-equilibration. Identification and quantification were performed using retention times and calibration curves of standard glucosinolates (glucoraphanin, sinigrin, gluconapin, gluconasturtiin). Other glucosinolates were relatively quantified according to ISO 9167-1, and results were expressed as pmol/g dry weight.

2.6. Antioxidant activity assays

The radical scavenging activity of kale extracts was determined using the DPPH assay (Cheung et al., 2003). Equal volumes (100 μL each) of kale extract and 0.2 mM DPPH solution were mixed in a 96-well plate and incubated

at 37℃ for 30 min. Absorbance was measured at 515 nm, and DPPH radical scavenging activity (%) was calculated as:

$$\text{DPPH radical scavenging activity (\%)} = (1 - Abs_{sample} / Abs_{control}) \times 100$$

ABTS radical scavenging activity was evaluated as described by Re et al. (1999), mixing 100 μL of extract with 100 μL of 0.2 mM ABTS solution and incubating for 30 min at 37℃ before measuring absorbance at 732 nm. ABTS radical scavenging activity (%) was calculated as:

$$\text{ABTS radical scavenging activity (\%)} = (1 - Abs_{sample} / Abs_{control}) \times 100$$

Reducing power was assessed according to Oyaizu (1986). Briefly, 1 mL of kale extract was mixed with 1 mL of phosphate buffer (200 mM, pH 6.6) and 1 mL of 1% potassium ferricyanide, incubated at 50℃ for 20 min, and then mixed with 1 mL of 10% trichloroacetic acid. The mixture was centrifuged at 13,500 ×*g* for 15 min, and the supernatant was combined with 1 mL of distilled water and 1 mL of ferric chloride solution. Absorbance was measured at 720 nm, with ascorbic acid used as a reference standard.

2.7. Statistical Analysis

All data were expressed as the mean±SD of three independent experiments. Statistical analyses were performed using R-Studio software (Version 3.5.1, Boston, MA, USA). One-way analysis of variance (ANOVA) was first conducted to examine significant differences among treatments. When significant differences were detected, Duncan's multiple range test was applied to determine pairwise differences among treatment means.

3. Results and discussion

3.1. Proximate composition

The proximate composition of kale cultivated under organic and conventional systems is presented in Table 1. The moisture content of conventionally grown kale ranged from 86.24% to 91.34%, while that of organically grown kale ranged from 88.30% to 89.60%. Although no substantial differences were observed, some conventional samples exhibited higher moisture levels than organic ones. These variations may reflect differences in soil water retention, harvest timing, and climatic conditions. Previous studies have reported that organic crops tend to grow more slowly, which can result in thicker cell walls and lower moisture retention (Chaudhary and Verma, 2018). Although the specific cultivation environment of the kale samples used in this study could not be verified, previous studies on cruciferous vegetables indicate that environmental factors such as light intensity, temperature, and nutrient availability can influence the biosynthesis of secondary metabolites (Salic and Samec, 2022).

Crude protein content was significantly higher in organic kale (0.51-0.61%) than in conventional kale (0.28-0.45%). This increase may result from the slow release of nitrogen in organic soils, which allows for sustained nitrogen availability, enhanced microbial activity, and improved nitrogen uptake efficiency in plants, thereby supporting greater protein accumulation (Chaudhary and Verma, 2018; Wang et al., 2023). Similarly, crude fat content was slightly higher in organic kale (1.02-2.36%) compared to conventional kale

Table 1. Proximate composition (%) of kale under conventional and organic cultivation systems

Samples		Moisture	Crude protein	Crude fat	Ash
Conventional	A	86.24±0.25[1)c2)]	0.44±0.06[c]	2.07±0.10[b]	2.07±0.10[b]
	B	90.69±0.26[a]	0.45±0.05[c]	2.04±0.01[b]	2.04±0.01[b]
	C	91.34±0.35[a]	0.28±0.02[d]	1.64±0.03[c]	1.64±0.03[c]
Organic	D	88.30±0.74[b]	0.53±0.06[b]	2.36±0.19[a]	2.36±0.19[a]
	E	89.60±0.38[b]	0.51±0.00[b]	1.02±0.07[d]	1.02±0.07[d]
	F	89.23±0.25[b]	0.61±0.06[a]	2.14±0.00[b]	2.14±0.00[b]

[1)]All values are mean±SD (n=3).
[2)]Means with different superscript letters ([a-d]) in the same column are significantly different ($p<0.05$) by Duncan's multiple range test.

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(1.64-2.07%), with the highest value observed in organic sample D (2.36%). Although leafy vegetables typically contain low levels of crude fat, enhanced photosynthesis and fatty acid biosynthesis have been suggested to occur under organic cultivation (Chaudhary and Verma, 2018).

Ash content, an indirect indicator of mineral levels, ranged from 1.64% to 2.07% in conventional kale and from 1.02% to 2.36% in organic kale. Greater variation was observed among organic samples, with the lowest value recorded in sample E (1.02%) and the highest in sample D (2.36%). This variability may be attributed to the use of organic fertilizers instead of chemical fertilizers, as the dynamics of soil microbial activity and mineral leaching can differ substantially in organic farming (Hernandez et al., 2021).

Supporting evidence from previous studies also indicates that organic vegetables generally exhibit higher proximate nutrient contents. Kim et al. (2004) reported that organic kale contained 20-70% higher levels of carotene, vitamins B_1, B_2, niacin, and vitamin C compared with conventionally grown kale, as well as approximately 17.9% higher mineral content (calcium, potassium, sodium, phosphorus). Similarly, Chaudhary and Verma (2018) observed higher protein, crude fat, and ash contents in organic kale than in conventional counterparts. These findings are consistent with the present study, further suggesting that symbiotic associations with nitrogen-fixing microorganisms and enhanced defense responses may increase amino acid metabolism in organically cultivated crops (Reganold and Wachter, 2016). Overall, organically cultivated kale contained higher protein and lipid levels and, in some cases, higher mineral and moisture contents, indicating that organic cultivation may positively influence plant metabolism and nutrient accumulation. However, these results may also be influenced by soil conditions, harvest timing, and varietal differences, highlighting the need for large-scale follow-up studies.

One limitation of this study is that the specific cultivar of kale used could not be verified, as the leaves were purchased from an online market without detailed information provided by the supplier. Considering that the cultivar may influence the biosynthesis and accumulation of secondary metabolites, future studies should compare multiple identified cultivars to better elucidate these differences.

3.2. Antioxidant compounds

The total polyphenol and flavonoid contents of kale were quantified and expressed as GAE and QE, respectively (Table 2). Total polyphenol content ranged from 238.56-287.97 μg GAE/g in conventional kale and 288.47-312.53 μg GAE/g in organic kale, with consistently higher values in organic samples.

Total flavonoid content also followed the same trend, ranging from 18.07-43.10 μg QE/g in conventional kale and 44.33-75.40 μg QE/g in organic kale. Notably, organic sample F exhibited the highest levels of both polyphenols (312.53 μg GAE/g) and flavonoids (75.40 μg QE/g), whereas conventional sample C showed the lowest values (238.56 μg GAE/g and 18.07 μg QE/g). These results suggest that cultivation practices influence the accumulation of phenolic and flavonoid compounds in kale.

The elevated levels of polyphenols and flavonoids in organic kale are consistent with previous studies. Faller and Fialho (2010) reported higher polyphenol contents in organic potatoes, broccoli, onions, tomatoes, and cabbages compared with conventional produce, attributing this to increased biotic and abiotic stress under organic conditions, which stimulates the biosynthesis of secondary metabolites such as phenolics. The markedly high flavonoid content in organic sample F (75.40 μg QE/g) may reflect exposure to more intense environmental stresses, as flavonoid synthesis is known to be induced by UV radiation, pest attacks, and mechanical injury (Zuchowski et al., 2011). Other reports also support this trend, noting that excessive nitrogen fertilization in conventional systems can suppress secondary metabolite production, whereas organic fertilization promotes polyphenol synthesis (Basay et

Table 2. Total polyphenol and flavonoid contents of kale under conventional and organic cultivation systems

Samples		Total polyphenols (μg GAE[1]/g)	Total flavonoids (μg QE[2]/g)
Conventional	A	287.97±4.95[3)b4)]	40.63±0.89[d]
	B	274.94±3.82[c]	43.10±1.52[c]
	C	238.56±1.98[d]	18.07±1.03[e]
Organic	D	304.90±10.13[a]	47.14±1.56[b]
	E	288.47±10.47[b]	44.33±1.22[c]
	F	312.53±8.35[a]	75.40±2.72[a]

[1)]GAE, gallic acid equivalent.
[2)]QE, quercetin equivalent.
[3)]All values are mean±SD (n=3).
[4)]Means with different superscript letters ([a-c]) in the same column are significantly different ($p<0.05$) by Duncan's multiple range test.

al., 2021). Similarly, Lee et al. (2015) demonstrated that organic spinach contained higher total flavonoid content than conventionally grown spinach when expressed as quercetin equivalents.

The β-carotene content of kale cultivated under organic and conventional practices was quantified by HPLC and is presented in Table 3. The β-carotene content of kale was also quantified using HPLC. Conventional kale contained 20.71-26.28 μg/g of β-carotene, whereas organic kale contained 25.53-31.02 μg/g, with the highest value recorded in organic sample F (31.02 μg/g) and the lowest in conventional sample C (20.71 μg/g). Overall, organic kale samples exhibited higher β-carotene levels. β-Carotene, a major carotenoid and provitamin A, contributes to vision, immune defense, and antioxidant protection in humans (Kim, 2020). In plants, it functions as an accessory pigment in photosynthesis and as a defense component against oxidative stress. Organic cultivation may enhance β-carotene accumulation due to greater exposure to natural light and reduced use of synthetic protective agents, which can upregulate carotenoid biosynthesis pathways (Stra et al., 2023). Additionally, increased environmental stress under organic conditions may activate the endogenous synthesis of carotenoids and other antioxidants (Cardoso et al., 2011). Previous studies also reported higher β-carotene concentrations in organically cultivated tomatoes and Brussels sprouts compared with conventional counterparts (Caris-Veyrat et al., 2004; Kapusta-Duch and Leszczynska, 2013), supporting the current findings. Nonetheless, β-carotene levels are influenced by multiple factors, including cultivar, maturation stage, climate, agricultural practices, and postharvest storage conditions, and its degradation is accelerated by heat, light, and oxygen (Cardoso et al., 2011; Kapusta-Duch and Leszczynska, 2013).

Table 3. β-Carotene content of kale under conventional and organic cultivation systems

Samples		β-carotene (μg/g)
Conventional	A	22.83±1.20[1)d2)]
	B	26.28±1.43[c]
	C	20.71±0.20[c]
Organic	D	25.53±0.41[c]
	E	29.79±0.26[b]
	F	31.02±1.37[a]

[1)]All values are mean±SD (n=3).
[2)]Means with different superscript letters ([a-c]) in the same column are significantly different ($p<0.05$) by Duncan's multiple range test.

3.3. Glucosinolate content

The representative HPLC chromatogram of glucosinolates obtained from organically and conventionally cultivated kale is shown in Fig. 1. Six individual glucosinolates, namely glucoiberverin, gluconapin, gluconasturtin, glucoerucin, glucobrassicin, and 4-methoxyglucobrassicin, were identified from each sample. The glucosinolate profiles of kale cultivated under conventional and organic systems are summarized in Table 4. In most cases, organic samples exhibited higher glucosinolate levels than conventional ones. Gluconapin content was measured 29.18-36.72 pmol/g in conventional kale, whereas 37.41-41.18 pmol/g in organic samples, indicating a significant increase. Glucoiberverin and glucoerucin were slightly higher in some organic samples but showed relatively small variation overall. Glucobrassicin and gluconasturtiin were consistently higher in organic kale, with sample F exhibiting the highest concentrations (5.24 and 12.78 pmol/g, respectively). Likewise, 4-methoxyglucobrassicin was higher in all organic samples, with sample E showing the highest value (14.74 pmol/g).

Glucosinolates are sulfur-containing secondary metabolites abundant in cruciferous vegetables, consisting of a β-D-thioglucose group, a sulfonated oxime group, and variable side chains (Fahey et al., 2003). Kale is particularly rich in gluconapin, gluconaphanin, sinigrin, glucoiberverin, glucoerucin, glucobrassicin, gluconasturtiin, and 4-methoxyglucobrassicin, all of which contribute to its antioxidant and chemopreventive potential (Hwang et al., 2019). The higher glucosinolate levels in organic kale observed in this study are consistent

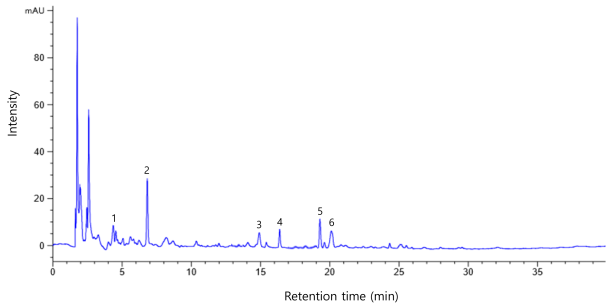

Fig. 1. Typical HPLC chromatogram of desulfated glucosinolate isolated from kale. 1, glucoiberverin; 2, gluconapin; 3, gluconasturtin; 4, glucoerucin; 5, glucobrassicin; 6, 4-methyoxyglucobrassicin.

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Table 4. Glucosinolate content (pmol/g dry weight) of kale under conventional and organic cultivation systems

Glucosinolates	Conventional			Organic		
	A	B	C	D	E	F
Gluconapin	29.18±1.57[1)d2)]	36.72±1.12[c]	35.89±2.25[c]	38.41±2.78[b]	41.18±3.36[a]	37.73±1.53[b]
Glucoiberverin	9.16±0.95[c]	10.54±0.85[b]	9.15±0.75[c]	10.95±0.67[b]	11.87±0.92[a]	10.45±0.74[b]
Glucoerucin	10.43±0.87[c]	10.03±0.94[c]	9.57±0.75[d]	11.87±1.05[b]	13.25±0.98[a]	11.78±1.53[b]
Glucobrassicin	4.15±0.42[c]	4.16±0.37[c]	4.27±0.38[c]	4.92±0.63[b]	4.91±0.54[b]	5.24±0.42[a]
Gluconasturtin	11.25±0.83[c]	11.94±1.07[b]	11.83±1.41[b]	11.89±1.20[b]	12.01±1.83[a]	12.78±1.20[a]
4-Methyoxyglucobrassicin	12.41±1.74[c]	12.67±1.93[c]	13.16±1.62[b]	13.52±1.36[b]	14.74±2.04[a]	14.03±1.36[a]

[1)]All values are mean±SD (n=3).
[2)]Means with different superscript letters ([a-d]) in the same column are significantly different ($p<0.05$) by Duncan's multiple range test.

with previous findings. According to Eugui et al. (2023), the aliphatic glucosinolate content in organically grown broccoli was 27.62 μmol/g, which was approximately 54.82% higher than that in conventionally grown broccoli (17.84 μmol/g). Similarly, the total glucosinolate contents were 30.47 μmol/g in conventionally grown and 39.85 μmol/g in organically grown broccoli, indicating that the organic samples contained about 30.78% higher total glucosinolates ($p<0.05$). This trend has been interpreted as a consequence of increased environmental stress under organic conditions, which promotes the biosynthesis of defensive secondary metabolites. However, inconsistent findings have also been reported. For instance, Camara-Martos et al. (2022) found that the total glucosinolate content in organically grown turnip greens was 13.23 μmol/g, whereas conventionally grown samples ranged from 16.54-21.28 μmol/g. The aliphatic glucosinolate content, calculated as the sum of progoitrin, gluconapin, and glucobrassicanapin, was 12.56 μmol/g in organic turnip greens, while conventionally grown samples ranged from 14.80-20.54 μmol/g. Such discrepancies may result from complex factors including soil characteristics, cultivar, climate, harvest stage, and myrosinase activity (Eugui et al., 2023; Hallmann et al., 2017). In the present study, compounds such as glucoerucin and glucoiberverin showed inconsistent patterns between cultivation systems or high sample-to-sample variation, suggesting that their metabolic pathways may be particularly sensitive to specific environmental factors.

3.4. Antioxidant activity

The antioxidant activities of conventional and organic kale were evaluated using DPPH and ABTS radical scavenging assays and reducing power (Table 5). DPPH radical scavenging activity ranged from 59.55 to 60.16% in conventional kale and from 62.01 to 64.59% in organic kale, indicating generally higher activity in the latter. ABTS radical scavenging activity also showed a slight increase in organic samples, ranging from 75.76 to 76.09%, compared with 65.87 to 71.88% in conventional kale.

Reducing power, expressed as absorbance at 720 nm, ranged from 0.70 to 0.83 in conventional kale and from 0.85 to 0.95 in organic kale. Organic sample F exhibited the highest reducing power (0.95). Collectively, all three assays demonstrated that organic kale possessed superior antioxidant activity compared with conventional kale.

Antioxidant activity in vegetables is closely associated with bioactive constituents such as polyphenols, flavonoids, vitamin C, and carotenoids. In this study, the higher levels of these compounds in organic kale were accompanied by stronger antioxidant capacity. Similar results were reported by Kim et al. (2014), who found that organic kale juice exhibited 4.9-8.7% greater radical scavenging activity (DPPH and nitric oxide) than conventional kale juice. Previous studies suggest that enhanced antioxidant activity in organic crops may result from exposure to higher levels of biotic and abiotic stress, which stimulate the activation of plant defense mechanisms and the biosynthesis of antioxidant compounds. Organic fertilizers not only improve soil biological activity but also enhance its chemical and physical properties, thereby supporting plant growth and yield (Shang et al., 2020). Furthermore, organic fertilizers promote nutrient cycling and contribute positively to global food production systems (Timsina, 2018). Several reports have confirmed that organic

Table 5. Antioxidant activity of kale under conventional and organic cultivation systems

Samples		DPPH radical scavenging activity (%)	ABTS radical scavenging activity (%)	Reducing power
Conventional	A	59.82±0.75[1)c2)]	71.88±0.68[b]	0.80±0.01[d]
	B	59.55±0.42[c]	68.96±1.74[c]	0.83±0.01[c]
	C	60.16±0.54[c]	65.87±1.47[d]	0.70±0.00[e]
Organic	D	63.42±0.40[a]	75.79±0.55[a]	0.85±0.00[bc]
	E	62.01±0.60[b]	75.76±0.62[a]	0.86±0.03[b]
	F	64.59±1.83[a]	76.09±0.50[a]	0.95±0.01[a]

[1)]All values are mean±SD (n=3).
[2)]Means with different superscript letters ([a-e]) in the same column are significantly different ($p<0.05$) by Duncan's multiple range test.

fertilizers increase antioxidant capacity and the accumulation of secondary metabolites such as flavonoids, phenolics, lycopene, and β-carotene compared with conventional systems (Aina et al., 2019; Dumas et al., 2003). Chang and Kim (2016) also demonstrated significantly higher DPPH scavenging activity in organically grown broccoli, cabbage, and perilla leaves compared with conventional counterparts, although ABTS activity showed mixed results depending on the crop. For example, according to Chang et al. (2015), the DPPH radical scavenging activity was higher in organically grown green chili peppers (64.10%) than in conventionally grown ones (62.72%), showing a statistically significant difference ($p<0.001$). In contrast, the ABTS radical scavenging activity was higher in conventionally grown green chili peppers (52.86%) compared to organic samples (51.06%), also exhibiting a statistically significant difference ($p<0.001$).

These findings indicate that antioxidant activity may vary depending on vegetable species, assay method, and extraction conditions. The DPPH assay primarily reflects lipophilic radical scavenging activity and is strongly associated with flavonoids and carotenoids (Cheung et al., 2003). In contrast, the ABTS assay can detect both hydrophilic and lipophilic antioxidant activity and correlates more closely with total polyphenols (Re et al., 1999). Reducing power reflects the electron-donating capacity of antioxidants and is linked to the levels of reductive compounds and antioxidant enzymes (Floegel et al., 2011; Oyaizu, 1986). Future studies should therefore compare bioactivity and antioxidant capacity across a wider range of crops under different cultivation systems, with particular emphasis on the dual role of environmental stress in reducing crop quality while enhancing secondary metabolite production.

4. Conclusions

This study aimed to compare the proximate composition, bioactive metabolite contents, and antioxidant activities of kale (*Brassica oleracea* var. *acephala*) cultivated under organic and conventional farming systems, in order to elucidate the effects of cultivation practices on quality characteristics. Proximate analysis showed no substantial differences in moisture or ash contents between the two systems; however, crude protein was higher in organically grown kale, and crude fat was also slightly elevated. Total polyphenol content ranged from 238.56 to 287.97 μg GAE/g in conventional kale and from 288.47 to 312.53 μg GAE/g in organic kale, while total flavonoid content ranged from 18.07 to 43.10 μg QE/g in conventional samples compared with 44.33 to 75.40 μg QE/g in organic samples, indicating significantly higher levels in organic kale. β-Carotene contents were also higher in organic kale (25.53-31.02 μg/g) than in conventional kale (20.71-26.28 μg/g). In terms of glucosinolates, organic samples exhibited higher concentrations of gluconapin and 4-methoxyglucobrassicin. Antioxidant activity, as assessed by DPPH and ABTS radical scavenging assays and reducing power, was consistently greater in organic kale, which was strongly associated with its higher levels of polyphenols, flavonoids, and β-carotene. Collectively, these findings demonstrate that organically cultivated kale exhibits superior accumulation of bioactive metabolites and enhanced antioxidant activity compared with conventionally cultivated kale, thereby offering distinct nutritional and functional value. The results provide scientific evidence supporting the potential of organic cultivation for the production of high-functional vegetables, contributing both to

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consumer health promotion and to the advancement of sustainable agriculture.

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Conflict of interests

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Author contributions

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Ethics approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

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