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육종 소재 선발을 위한 대추 유전자원의 특성 조사 및 기능성 성분 분석

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Characterization and Bioactive Compound Analysis of 30 Jujube (*Ziziphus jujuba* Mill.) Accessions for Breeding Resource Development

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ABSTRACT

Background: Jujube (*Ziziphus jujuba* Mill.) is a premier medicinal crop with a long history in traditional medicine, valued for its diverse pharmacological properties. Although the industrial demand for high-value bioactive materials is rising, the Korean jujube industry remains vulnerable because of its narrow genetic base. In this study, we evaluated 30 jujube accessions to identify superior genetic resources for the development of medicinal and functional cultivars.
Methods and Results: Morphological traits, fruit quality, and antioxidant compounds were assessed over two consecutive years (2022 and 2023). 'Gwangam' produced the heaviest fruit (29.5 g), whereas 'Wolchul-60' exhibited the highest total soluble solids (29.4 °Brix). Physicochemically, 'Sanjo' recorded the highest vitamin C (1,472.5 mg/100 g DW) and total phenolic contents (TPC; 1,325.3 mg GAE/100 g DW), consequently displaying the strongest DPPH and ABTS radical-scavenging activities. Antioxidant capacity highly correlated with vitamin C content ($p < 0.001$). Fruit weight was negatively associated with antioxidant-related traits ($r = -0.61$ to -0.64, $p < 0.001$).
Conclusions: The large-fruited 'Gwangam,' high-sugar 'Wolchul-60,' and vitamin C- and TPC-rich 'Sanjo' represent promising breeding materials for developing high-value jujube cultivars with enhanced functional quality.

Key Words: Jujube, Antioxidant Activity, Functional Compound, Genetic Resources, Titratable Acidity, Vitamin C

INTRODUCTION

Chinese jujube (*Ziziphus jujuba* Mill.; Rhamnaceae) is a deciduous broadleaf fruit tree native to Asia, including China and Korea, with a cultivation history of more than 4,000 years. Owing to its strong environmental adaptability and high nutritional value, jujube has long been utilized as an important food and medicinal resource, and its production and consumption have recently expanded worldwide, including to Turkey, Romania, and Australia (Liu *et al*., 2020). With increasing consumer demand for natural antioxidants and functional foods, jujube is now gaining renewed attention as a

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high-value crop beyond conventional fresh-fruit use (Kim *et al*., 2021a; Park *et al*., 2023; Lee *et al*., 2025).

Jujube contains diverse bioactive constituents not only in fruit but also in other plant parts, including leaves, seeds, and bark. Jujube leaves have been reported to contain functional compounds such as vitamin C, rutin, and quercetin (Jin *et al*., 1999; Kim *et al*., 2011; Zhang *et al*., 2019), while the seeds within the stone are known to accumulate bioactives including saponin-related constituents (jujuboside A and B) and spinosin (Hua *et al*., 2022; Ruan *et al*., 2024). Bioactivities of bark-derived betulinic acid, including antiviral effects, have also been reported (Lee *et al*., 2008). In addition, previous studies have shown that jujube pulp is rich in sugars and organic acids as well as various functional constituents such as vitamin C, polyphenols, flavonoids, and cyclic AMP (cAMP) (Han *et al*., 2015; Ko *et al*., 2021; Park *et al*., 2021; Lee *et al*., 2025; Oh *et al*., 2025b).

Accordingly, the industrial importance of jujube has continued to increase alongside the rapidly growing demand for health functional foods. In the past, jujube was used mainly as a raw material for simple processed products such as dried jujube, chips, and juice (Bang *et al*., 2020). More recently, however, consumer perceptions have shifted positively toward fresh jujube with high sweetness and desirable texture, and jujube has gained attention as a high-income crop (Lee *et al*., 2018; Park *et al*., 2023). Consistent with this trend, new growers have continued to enter production; over the past five years (2020–2024), the number of farm households reached 52,145, increasing by approximately 9,700, and the cultivation area approached 6,487.2 ha (MAFRA, 2024). As of 2024, production totaled 7,666 tons, establishing jujube as a major forest product in Korea (KFS, 2025).

Despite this quantitative growth, the Korean jujube industry remains vulnerable due to its narrow genetic base. Commercial production is currently concentrated on a limited number of cultivars, including the standard jujube cultivar ‘Bokjo’ and several large-fruited cultivars such as ‘Hwangsil’ and ‘Cheonhwang’ (Oh *et al*., 2020; Kim *et al*., 2021a). This cultivar dependence has raised concerns regarding reduced resilience to emerging pests and diseases and to weather-related disasters under climate change (Lee *et al*., 2025; Oh *et al*., 2025b).

To mitigate this cultivar bias, the development of new cultivars using diverse genetic resources is essential. However, jujube exhibits a strong tendency toward parthenocarpy, which limits seed set and makes it difficult to obtain sufficient seeds through controlled hybridization (Ackerman, 1961). In Korea, several major registered cultivars, including ‘Cheonsang’ and ‘Cheonhwang’, have been reported to originate largely from bud-sport mutations rather than from conventional cross-breeding (NFSVC, 2024). Moreover, past breeding efforts have mainly focused on improving external market traits such as large fruit size and high soluble solids content in cultivars such as ‘Mudeung’ and ‘Geumseong’ (Oh *et al*., 2020), which has constrained the development of cultivars optimized for medicinal and functional attributes. Although molecular marker studies aimed at characterizing genetic diversity have recently expanded (Nam, 2016; Oh, 2019; Kim *et al*., 2021b; Kim *et al*., 2024), studies directly supporting practical crossing programs—particularly parental selection and trait–trait relationship analyses—remain limited.

Therefore, to improve crossing efficiency and to develop high-functionality cultivars, it is necessary to conduct detailed evaluations of seed formation capacity (kernel presence rate), growth traits, and functional constituents across diverse jujube accessions collected from domestic and international sources (Oh *et al*., 2020; Lee *et al*., 2025; Oh *et al*., 2025b). Broad trait evaluation and the selection of superior accessions while maintaining genetic diversity will provide a foundation for developing high-value materials and enhancing resilience under future climatic conditions (Gao *et al*., 2012; Liu *et al*., 2020; Oh *et al*., 2020).

Accordingly, this study compared fruit quality traits and antioxidant activities among 30 jujube accessions and examined correlations among key traits relevant to breeding, thereby providing baseline information for future cultivar development and functional utilization of jujube.

MATERIALS AND METHODS

1. Plant materials

Thirty jujube genetic resources were evaluated over two consecutive years (2022-2023) (Table 1). The materials consisted of 8–10-year-old trees maintained in the resource preservation orchard of the Jujube Research Institute, Chungcheongbuk-do Agricultural Research and Extension Services (36°34′38.7″ N, 127°44′44.9″ E). Trees were spaced at 4 m × 2 m and managed under standard commercial practices for fertilization and pest and disease control in Korea. The 30 accessions were selected based on prior field observations and published reports describing

Table 1. General information and phenological traits of 30 jujube genetic resources evaluated over two years (2022–2023).

Genetic resources	IT No.[1)]	Accession No.[2)]	Origin[3)]	Phenological traits[4)]			
				Bud burst date	Flowering date	Harvest date	Blooming type
Ja-2	233590	CBJ0001	KOR	18-Apr	14-Jun	06-Oct	A
Jc-28a	233591	CBJ0002	KOR	22-Apr	12-Jun	10-Oct	M
Jh-16	317174	CBJ0025	KOR	22-Apr	15-Jun	06-Oct	A
Cheonsang	317182	CBJ0038	KOR	21-Apr	16-Jun	03-Oct	A
Sangwangbyeoni	317185	CBJ0041	KOR	22-Apr	16-Jun	13-Oct	A
Bokjobyeoni	317186	CBJ0042	KOR	22-Apr	11-Jun	08-Oct	A
Mudeung-60	317187	CBJ0043	KOR	20-Apr	15-Jun	12-Oct	A
Wolchul-60	317189	CBJ0045	KOR	20-Apr	14-Jun	11-Oct	A
Wolchul-80	317190	CBJ0046	KOR	20-Apr	13-Jun	11-Oct	A
Bokjo-60	317191	CBJ0047	KOR	19-Apr	15-Jun	12-Oct	A
Bokjo-80	317192	CBJ0048	KOR	20-Apr	15-Jun	11-Oct	A
Uiseong-5	317396	CBJ0052	KOR	16-Apr	15-Jun	10-Oct	A
Uiseong-15	317205	CBJ0061	KOR	19-Apr	16-Jun	10-Oct	A
Cheonhwang	317216	CBJ0072	KOR	20-Apr	12-Jun	13-Oct	A
Hwangsil	317219	CBJ0075	KOR	20-Apr	12-Jun	14-Oct	A
Wangdaechu	317226	CBJ0082	CHN	20-Apr	15-Jun	05-Oct	A
Uiseong-B	317233	CBJ0089	KOR	20-Apr	15-Jun	04-Oct	M
Uiseong-C	317234	CBJ0090	KOR	20-Apr	16-Jun	05-Oct	M
Sanjo	317236	CBJ0092	KOR	20-Apr	05-Jun	24-Sep	M
6wolseonjo	317245	CBJ0101	CHN	20-Apr	19-Jun	30-Sep	A
Wolgwang	317246	CBJ0102	CHN	17-Apr	08-Jun	30-Sep	A
Muhaekhongjo	317247	CBJ0103	CHN	20-Apr	13-Jun	02-Oct	M
Geumchang1ho	317248	CBJ0104	CHN	22-Apr	19-Jun	01-Oct	A
Be-6	317253	CBJ0109	CHN	16-Apr	16-Jun	30-Sep	M
Bokjo	317259	CBJ0115	KOR	19-Apr	12-Jun	10-Oct	A
Hongan	233624	CBJ0120	KOR	19-Apr	13-Jun	11-Oct	A
Bongmilgwanjo	317270	CBJ0136	CHN	20-Apr	12-Jun	15-Oct	A
Hongjinjujo	317274	CBJ0140	CHN	20-Apr	13-Jun	03-Oct	A
Sahongdaejo	317278	CBJ0144	CHN	16-Apr	13-Jun	15-Oct	A
Gwangam	-	CBJ0166	KOR	20-Apr	15-Jun	15-Oct	A

[1)]IT No. denotes introduction (permanent registration) numbers assigned by the National Agrobiodiversity Center, RDA, Republic of Korea. [2)]Accession No. indicates accession numbers assigned by the Jujube Research Institute. [3)]Origin: KOR, Republic of Korea; CHN, China. [4)]Phenological traits were evaluated over two consecutive growing seasons (2022–2023) using standard field criteria: bud burst date (bud growth ≥ 1 mm), flowering date (> 10% crown blooming), and harvest date (> 70% fruit coloration). The presented data represent the average values across the two years. Blooming type: M, Morning flowering; A, Afternoon flowering. "–" indicates not assigned.

diversity in growth vigor, fruit size, and yield-related traits, to represent genetically and agronomically diverse materials.

Phenological and morphological traits were assessed according to the Research Standards for Agricultural Science and Technology Investigation and Analysis (RDA, 2012) and the Jujube Tree Characteristic Survey Guidelines (NFSVC, 2009). Flowering type was classified as morning- or afternoon-flowering based on the timing of sepal opening (Nam *et al*., 2015; Yao *et al*., 2015). In each year, three trees per accession were used as biological replicates (n = 3 per year). Different trees were sampled in 2022 and 2023, and tree-year means were used as analytical units for pooled comparisons, as described in the Statistical analysis section.

Leaves were collected in mid-July from fully expanded mature leaves at the middle portion of fruiting shoots (3rd–5th nodes). Fruits and stones were harvested in early October at commercial maturity (≥ 70% skin coloration). Leaf length and width were measured using a ruler, and petiole length was measured using a digital caliper (CD-15 CPX, Mitutoyo, Kawasaki, Japan). Leaf greenness (SPAD value) was recorded using a portable chlorophyll meter (SPAD-502 Plus, Konica Minolta, Tokyo, Japan). Fruit and stone dimensions were measured using a digital caliper, and weights were recorded using an electronic balance (XT 4200C, Precisa, Dietikon, Switzerland). Fruit firmness was determined using a hardness tester (KM-5, Fujiwara, Tokyo, Japan) equipped with a 5-mm probe. Total soluble solids (TSS) (°Brix) were measured using a portable digital refractometer (PAL-1, ATAGO Co., Ltd., Tokyo, Japan). Kernel formation was evaluated by manually cracking stones and recording the presence of a fully developed kernel.

2. Sample preparation and extraction

For functional component analyses, fruit pulp samples were prepared by removing the seeds immediately after harvest, slicing the pulp, and storing the samples in a deep freezer at −80°C. The frozen pulp samples were then freeze-dried using a freeze dryer (MP-9015, Malda, Korea) by gradually increasing the temperature from −40°C to 20°C at 5°C intervals every 4 h for a total duration of 60 h (Oh, 2019; Oh *et al*., 2020). The dried samples were finely ground and passed through a 50-mesh sieve prior to extraction. Two grams of powdered sample were extracted with 18 mL of distilled water by shaking extraction for 2 h. The extracts were centrifuged at 4°C and 8,000 rpm for 20 min, and the supernatants were vacuum filtered through filter paper (No. 2, Advantec, Tokyo, Japan) to obtain analytical solutions (Park and Kim, 2016; Oh, 2019). In this study, a water-based extraction method was employed to evaluate the functional potential of jujube under conditions similar to food utilization environments. Vitamin C, a major functional indicator in jujube pulp, is water-soluble and can be rapidly oxidized in organic solvents; therefore, aqueous extraction is considered the most suitable method for maintaining compound stability. In addition, all resources were extracted under identical conditions to accurately compare functional differences among accessions (Adjdir *et al*., 2019; Ko *et al*., 2021).

3. Determination of pH and titratable acidity

Fruits exhibiting more than 70% skin coloration were harvested, and the pulp was juiced to obtain samples for pH and titratable acidity analyses. The pH of the juice was measured using a pH meter (Thermo Scientific Orion, Waltham, MA, USA), and calibration was performed to ensure that the electrode slope exceeded 96% prior to measurement. Titratable acidity was determined by diluting 5 mL of fruit juice with 5 mL of distilled water and titrating the mixture with 0.1 N NaOH solution to an endpoint of pH 8.2 (Shin *et al*., 2023).

Titratable acidity was calculated as malic acid equivalents (Tepe *et al*., 2022), based on the predominant organic acid reported in jujube, using the following equation:

$$Titratable\ Acidity\ (TA) = \frac{V \times f \times F}{S} \times 100(\%)$$

[V= volume of 0.1 N NaOH used for titration (mL); f= standardization factor of 0.1 N NaOH (1.001); F= organic acid conversion factor equivalent to 1 mL of 0.1 N NaOH (malic acid = 0.0067); S= sample volume (mL)]

4. Analysis of bioactive compounds

4.1. DPPH radical scavenging activity

DPPH radical scavenging activity was determined using a modified method of Blois (1958). A 0.2 mM DPPH reagent (DPPH from Sigma-Aldrich Co., St. Louis, MO, USA) was freshly dissolved in ethanol and kept in the dark during analysis. Prior to reaction, the jujube extract was diluted 400-fold with distilled water, and 0.2 mL of the diluted extract was mixed with 0.8 mL of the DPPH reagent in the dark and incubated for 30 min. The control consisted of distilled water mixed with the DPPH reagent under the same conditions. Absorbance of the reaction solution was measured at 525 nm using a UV–Vis spectrophotometer (Cary 100 UV–Vis, Agilent Technologies, Santa Clara, CA, USA), according to previously reported conditions (Kim *et al*., 2011; Oh, 2019; Oh *et al*., 2020; Jeong *et al*., 2023b; Kim *et al*., 2025).

DPPH radical scavenging activity was calculated using the following equation:

$$DPPH\ radical\ scavenging\ activity(\%) =$$
$$1 - \left(\frac{Absorbance\ of\ sample\ at\ 525\ nm}{Absorbance\ of\ control\ at\ 525\ nm}\right) \times 100$$

4.2. ABTS radical scavenging activity

ABTS radical scavenging activity was measured following the method described by Re et al. (1999). ABTS (7.4 mM, Sigma-Aldrich Co., St. Louis, MO, USA) and potassium persulfate (2.6 mM, Sigma-Aldrich Co., St. Louis, MO, USA) were dissolved in methanol and reacted in the dark for 24 h to generate ABTS radical cations. Prior to analysis, the jujube extract was diluted 100-fold with distilled water, and 50 μL of the diluted extract was mixed with 1 mL of the ABTS reagent in the dark and incubated for 30 min. The control consisted of distilled water mixed with the ABTS reagent under the same conditions. Absorbance was then recorded at 735 nm using a UV-Vis spectrophotometer, according to previously reported analytical procedures (Kim *et al*., 2011; Park and Kim, 2016; Park *et al*., 2017; Oh *et al*., 2025a).

ABTS radical scavenging activity was calculated using the following equation:

$$ABTS\ radical\ scavenging\ activity(\%) = 1 - \left(\frac{Absorbance\ of\ sample\ at\ 735nm}{Absorbance\ of\ control\ at\ 735nm}\right) \times 100$$

4.3. Contents of vitamin C, total phenolics (TPC), and total flavonoids (TFC)

The contents of vitamin C, total phenolics (TPC), and total flavonoids (TFC) were determined using freeze-dried fruit pulp samples submitted to the Comprehensive Analytical Testing Service of the Korea Agriculture Technology Promotion Agency (KOAT, Iksan, Korea). Analyses were conducted according to the official analytical methods of the Ministry of Food and Drug Safety (MFDS, 2023a; 2023b). Vitamin C was expressed as mg ascorbic acid per 100 g dry weight (DW), TPC as mg gallic acid equivalents (GAE) per 100 g DW, and TFC as mg quercetin equivalents (QE) per 100 g DW.

5. Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (Version 24.0; IBM Corp., Armonk, NY, USA). For pooled comparisons shown in the main tables, tree-year means from both years were used as analytical units ($n = 6$ per accession; 3 trees per year × 2 years), and differences among accessions were evaluated by one-way analysis of variance (ANOVA) followed by Tukey's HSD test at $p < 0.05$. Prior to ANOVA, residual normality and homogeneity of variance were assessed using the Shapiro–Wilk test and Levene's test, respectively. In addition, two-way ANOVA was conducted to evaluate the effects of accession, year, and accession × year interaction. To avoid pseudoreplication, subsample measurements within each tree were averaged to obtain tree-level means before statistical analysis. Pearson's correlation coefficients were calculated using accession-level mean values averaged over the two years (n = 30). Because the same accessions were evaluated across years, the pooled results were interpreted with consideration of annual variation.

RESULTS AND DISCUSSION

1. Growth and phenological characteristics of jujube accessions

Phenological stages are important indicators for selecting suitable cultivation areas and mitigating weather-related risks (Table 1). All phenological traits reported here were evaluated over two consecutive growing seasons (2022–2023), and the presented values are the two-year averages. Bud burst ranged from 16 April ('Uiseong-5') to 22 April ('Jc-28a'), representing an approximately 6-day variation among accessions. Flowering ranged from 5 June ('Sanjo') to 19 June ('6wolseonjo'). Compared with temperate fruit trees such as apple and peach, which typically bloom in mid- to late April and can be vulnerable to late frost damage (Yun *et al*., 2012; Han *et al*., 2016; Kweon and Sagong, 2022; Jeong *et al*., 2023a), the later flowering of jujube may reduce exposure to frost risk and thereby contribute to more stable fruit set under Korean conditions. Harvest timing also varied widely, from 24 September ('Sanjo', very early-maturing) to 15 October ('Gwangam', late-maturing), highlighting the value of these accessions for maturity diversification. Such variation may help reduce market oversupply during peak harvest and facilitate labor distribution in orchard operations (Yu and Kim, 2017). Blooming type classification showed that six accessions (including 'Sanjo') were morning-flowering, whereas 24 accessions (including 'Bokjo') were afternoon-flowering, consistent with previous reports that Korean-collected accessions predominantly exhibit the afternoon-flowering type (Nam *et al*., 2015; Oh, 2019; Oh *et al*., 2020). Although phenological traits were monitored over two years in this study, continued long-term monitoring will be valuable to further confirm the stability of accession differences under varying weather conditions.

2. Leaf traits of jujube accessions

Morphological and physiological characteristics of leaves, the primary photosynthetic organs, varied significantly among accessions (Table 2; Fig. 1). 'Cheonsang' exhibited the largest leaves (7.66 × 5.37 cm), representing a typical large-leaf type (Fig. 1A), whereas 'Sanjo' was classified as a small-leaf type (Fig. 1C). The leaf morphology index (LMI) ranged from 1.43 (ovate type) to 2.44 (lanceolate type), consistent with previous

Table 2. Leaf morphological traits and SPAD values of 30 jujube accessions.

Accession No.[1)]	Length (cm)	Width (cm)	LMI[2)]	Petiole length (cm)	SPAD value	Shape	Margin	Base
CBJ0001	6.90 ± 0.14^{abcdefg}	3.81 ± 0.11^{cdef}	1.81 ± 0.03^{hij}	0.45 ± 0.02^{defgh}	36.9 ± 1.57^{efghijk}	Elliptic	Crenate	Round
CBJ0002	6.74 ± 0.24^{bcdefgh}	3.19 ± 0.10^{ghi}	2.11 ± 0.11^{bcd}	0.69 ± 0.07^{ab}	44.4 ± 2.07^{bc}	Lanceolate	Crenate	Round
CBJ0025	5.39 ± 0.14^{klm}	3.10 ± 0.07^{hi}	1.75 ± 0.07^{ij}	0.61 ± 0.03^{bcde}	38.3 ± 2.32^{defghij}	Elliptic	Crenate	Round
CBJ0038	7.66 ± 0.38^{abc}	5.37 ± 0.44^{a}	1.43 ± 0.06^{k}	0.60 ± 0.03^{bcde}	39.7 ± 1.13^{defghi}	Ovate	Serrate	Round
CBJ0041	6.44 ± 0.50^{defghij}	3.75 ± 0.07^{cdefg}	1.73 ± 0.14^{ij}	0.67 ± 0.10^{abc}	41.1 ± 1.26^{cde}	Elliptic	Crenate	Acute
CBJ0042	7.12 ± 0.88^{abcdef}	4.41 ± 0.58^{b}	1.62 ± 0.04^{jk}	0.64 ± 0.12^{bcd}	39.2 ± 1.44^{defghij}	Ovate	Crenate	Acute
CBJ0043	6.30 ± 0.42^{fghijk}	3.33 ± 0.16^{fgh}	1.90 ± 0.11^{cdefghi}	0.33 ± 0.10^{ghi}	38.1 ± 0.87^{defghij}	Elliptic	Serrate	Round
CBJ0045	6.03 ± 0.18^{ghijkl}	3.30 ± 0.11^{fghi}	1.83 ± 0.07^{ghij}	0.32 ± 0.15^{hi}	35.6 ± 1.18^{ijk}	Elliptic	Serrate	Round
CBJ0046	6.41 ± 0.58^{efghijk}	3.45 ± 0.27^{defgh}	1.86 ± 0.04^{efghij}	0.43 ± 0.06^{efgh}	35.2 ± 2.44^{jk}	Elliptic	Serrate	Acute
CBJ0047	7.80 ± 0.49^{a}	4.20 ± 0.37^{bc}	1.86 ± 0.06^{efghi}	0.50 ± 0.10^{bcdefgh}	38.4 ± 1.71^{defghij}	Elliptic	Crenate	Round
CBJ0048	7.41 ± 0.72^{abcde}	3.93 ± 0.42^{bcde}	1.89 ± 0.04^{defghi}	0.50 ± 0.19^{cdefgh}	35.8 ± 1.26^{hijk}	Elliptic	Serrate	Round
CBJ0052	6.50 ± 0.20^{defghij}	3.46 ± 0.10^{defgh}	1.89 ± 0.06^{defghi}	0.39 ± 0.03^{fghi}	33.6 ± 1.58^{k}	Elliptic	Crenate	Acute
CBJ0061	6.69 ± 0.42^{cdefgh}	3.79 ± 0.26^{cdef}	1.77 ± 0.06^{ij}	0.66 ± 0.05^{abc}	36.9 ± 1.11^{efghijk}	Elliptic	Crenate	Acute
CBJ0072	6.12 ± 0.21^{fghijkl}	3.29 ± 0.16^{fghi}	1.87 ± 0.09^{efghi}	0.64 ± 0.06^{bcd}	37.2 ± 2.42^{efghijk}	Elliptic	Serrate	Round
CBJ0075	5.51 ± 0.59^{jklm}	3.10 ± 0.33^{hi}	1.79 ± 0.09^{hij}	0.46 ± 0.09^{defgh}	40.4 ± 1.87^{cdefg}	Elliptic	Serrate	Round
CBJ0082	5.64 ± 0.12^{ijklm}	2.37 ± 0.06^{jk}	2.39 ± 0.08^{a}	0.51 ± 0.04^{bcdefg}	38.6 ± 1.12^{defghij}	Lanceolate	Serrate	Acute
CBJ0089	6.96 ± 0.75^{abcdefg}	3.28 ± 0.27^{fghi}	2.14 ± 0.11^{bc}	0.55 ± 0.10^{bcdef}	44.5 ± 1.31^{abc}	Elliptic	Serrate	Acute
CBJ0090	6.49 ± 0.22^{defghij}	3.10 ± 0.19^{hi}	2.10 ± 0.15^{bcde}	0.50 ± 0.03^{bcdefgh}	44.5 ± 1.44^{abc}	Elliptic	Crenate	Round
CBJ0092	3.02 ± 0.40^{n}	1.46 ± 0.05^{l}	2.09 ± 0.30^{bcdef}	0.22 ± 0.05^{i}	48.7 ± 2.49^{a}	Elliptic	Serrate	Acute
CBJ0101	5.12 ± 0.22^{lm}	2.33 ± 0.16^{jk}	2.21 ± 0.20^{ab}	0.45 ± 0.06^{defgh}	40.0 ± 0.31^{defgh}	Elliptic	Serrate	Acute
CBJ0102	6.57 ± 0.72^{defghi}	2.75 ± 0.27^{ij}	2.40 ± 0.10^{a}	0.53 ± 0.16^{bcdef}	40.7 ± 2.41^{cdef}	Lanceolate	Crenate	Acute
CBJ0103	7.48 ± 0.15^{abcd}	3.41 ± 0.08^{efgh}	2.20 ± 0.03^{ab}	0.60 ± 0.05^{bcde}	39.2 ± 1.46^{defghij}	Elliptic	Crenate	Acute
CBJ0104	5.75 ± 0.32^{hijklm}	2.37 ± 0.14^{jk}	2.43 ± 0.06^{a}	0.51 ± 0.04^{bcdefg}	39.4 ± 2.33^{defghij}	Lanceolate	Serrate	Acute
CBJ0109	7.76 ± 0.49^{ab}	3.54 ± 0.15^{defgh}	2.21 ± 0.18^{ab}	0.63 ± 0.06^{bcd}	44.5 ± 2.21^{bc}	Elliptic	Serrate	Round
CBJ0115	7.44 ± 0.20^{abcde}	4.00 ± 0.13^{bcd}	1.86 ± 0.03^{efghij}	0.52 ± 0.07^{bcdefg}	35.8 ± 0.74^{hijk}	Elliptic	Serrate	Round
CBJ0120	7.41 ± 0.10^{abcde}	4.00 ± 0.08^{bcd}	1.85 ± 0.03^{fghij}	0.62 ± 0.03^{bcd}	36.2 ± 1.03^{ghijk}	Elliptic	Serrate	Round
CBJ0136	4.71 ± 0.33^{m}	1.95 ± 0.13^{kl}	2.44 ± 0.20^{a}	0.63 ± 0.07^{bcd}	36.7 ± 2.68^{fghijk}	Lanceolate	Serrate	Round
CBJ0140	4.73 ± 0.29^{m}	2.34 ± 0.12^{jk}	2.02 ± 0.06^{bcdefgh}	0.58 ± 0.02^{bcdef}	41.9 ± 1.81^{cd}	Elliptic	Serrate	Acute
CBJ0144	6.93 ± 1.24^{abcdefg}	3.38 ± 0.69^{efgh}	2.07 ± 0.09^{bcdefg}	0.84 ± 0.16^{a}	46.5 ± 4.62^{ab}	Elliptic	Crenate	Round
CBJ0166	5.99 ± 0.25^{ghijkl}	3.51 ± 0.14^{defgh}	1.71 ± 0.03^{ij}	0.59 ± 0.10^{bcde}	40.3 ± 1.94^{cdefg}	Elliptic	Crenate	Acute

[1)]Accession No. indicates accession numbers assigned by the Jujube Research Institute. [2)]LMI, leaf morphological index (leaf length / leaf width). Values are presented as mean ± SD based on tree-year means ($n = 6$ per accession; 3 trees per year × 2 years). Each tree-year value was calculated as the mean of 30 subsamples. Different letters within a column indicate significant differences among accessions according to Tukey's HSD test ($p < 0.05$).

reports (Jang *et al*., 2006; Li *et al*., 2015; Nam, 2016; Oh, 2019; Oh *et al*., 2020). Notably, 'Sanjo' showed the highest SPAD value (48.70), despite its small leaf size, indicating a relatively high leaf-greenness or chlorophyll-related index. Previous studies have reported nutritional and bioactive compounds in jujube leaves (Jin *et al*., 1999; Zhang *et al*., 2019). However, because SPAD is an indirect chlorophyll-related index and leaf bioactive compounds were not analyzed in this study, this result should not be interpreted as direct evidence of functional material potential. Further studies involving chlorophyll quantification, photosynthetic measurements, and leaf antioxidant profiling are needed to evaluate the functional value of jujube leaves.

3. Fruit morphological and quality traits of jujube accessions

Fruit appearance and quality traits, which are closely associated with consumer preference, differed markedly among

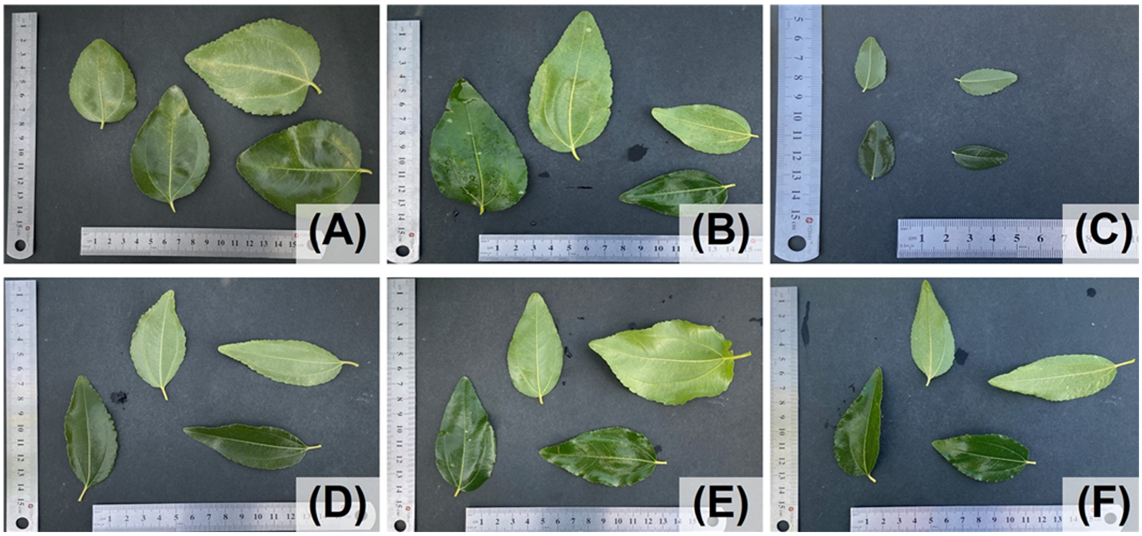

Fig. 1. Morphological characteristics of leaves in selected jujube accessions. Representative leaves showing variation in shape and size: (A) CBJ0038 (Cheonsang), (B) CBJ0047 (Bokjo-60), (C) CBJ0092 (Sanjo), (D) CBJ0104 (Geumchang1ho), (E) CBJ0115 (Bokjo), and (F) CBJ0136 (Bongmilgwanjo). A ruler in each photograph indicates scale (cm).

accessions (Table 3; Fig. 2). 'Uiseong-B' had the greatest fruit length (45.2 mm; Fig. 2B), whereas 'Hwangsil' showed the greatest fruit width (38.5 mm; Fig. 2A), representing large-fruit phenotypes. In contrast, 'Sanjo' had the smallest fruit dimensions (16.6 × 16.6 mm; Fig. 2C). These differences were reflected in fruit weight: 'Gwangam' produced the heaviest fruits (29.5 g; Fig. 2F), whereas 'Sanjo' averaged 2.4 g, indicating an approximately 12.3-fold difference among accessions. This pattern is consistent with the concept that fruit enlargement has been a key target trait during domestication and improvement of jujube (Liu *et al.*, 2020; Hua *et al.*, 2022). The fruit morphology index (FMI) ranged from 1.01 (round type) to 1.90 (conical type). Fruit firmness also differed among accessions, with 'Wangdaechu' showing the lowest firmness (2.3 kg/5 mm). Regarding internal quality, total soluble solids (TSS) were highest in 'Wolchul-60' (29.4 °Brix) and 'Bongmilgwanjo' (29.3 °Brix). Overall trends in major fruit traits were generally consistent with previous reports; however,

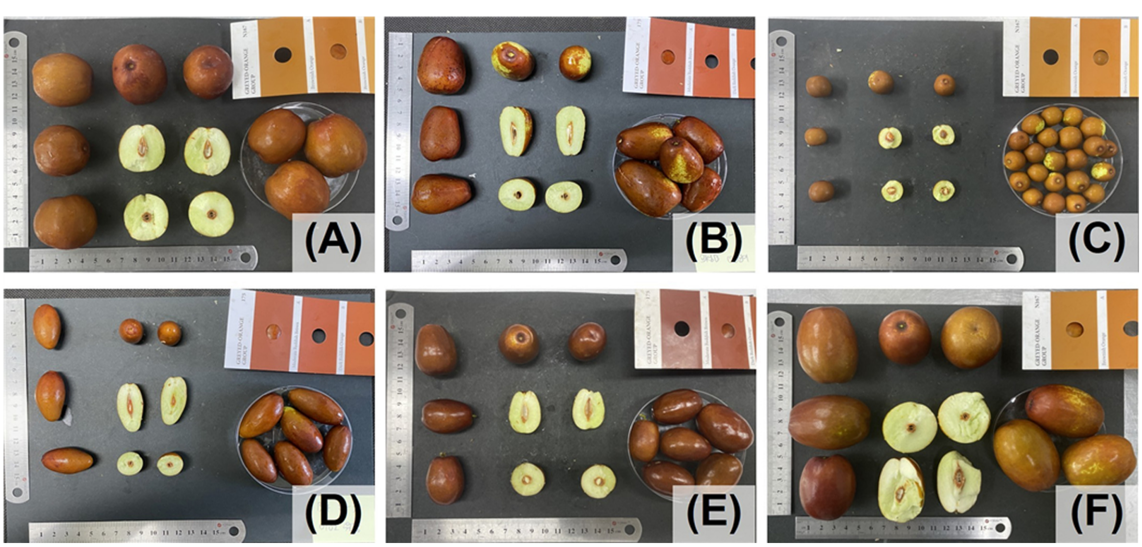

Fig. 2. Morphological characteristics of fruits in selected jujube accessions. Representative fruits showing variation in external shape, size, skin coloration, and internal structure: (A) CBJ0075 (Hwangsil), (B) CBJ0089 (Uiseong-B), (C) CBJ0092 (Sanjo), (D) CBJ0102 (Wolgwang), (E) CBJ0115 (Bokjo), and (F) CBJ0166 (Gwangam). A ruler in each photograph indicates scale (cm).

Table 3. Fruit morphological and quality traits of 30 jujube accessions.

Accession No.[1)]	Length (mm)	Width (mm)	FMI[2)]	Firmness (kg/5 mm)	Weight (g)	TSS (°Brix)	Shape
CBJ0001	35.7 ± 0.80[gh]	27.8 ± 0.54[ghij]	1.29 ± 0.02[defg]	3.09 ± 0.08[abcd]	13.0 ± 0.58[efg]	25.2 ± 0.67[bcdefg]	Cylindrical
CBJ0002	27.5 ± 0.15[k]	24.9 ± 0.41[ijkl]	1.11 ± 0.01[ijklm]	3.27 ± 0.15[ab]	8.8 ± 0.26[gh]	27.9 ± 1.36[abc]	Oblate
CBJ0025	37.1 ± 3.88[efgh]	36.1 ± 3.99[abc]	1.03 ± 0.02[lm]	3.11 ± 0.08[abc]	20.9 ± 6.72[cd]	26.2 ± 2.11[abcdefg]	Oblate
CBJ0038	36.3 ± 1.98[gh]	31.1 ± 2.12[defg]	1.17 ± 0.05[hij]	2.99 ± 0.06[abcd]	17.8 ± 2.78[de]	26.3 ± 1.07[abcdefg]	Ovate
CBJ0041	41.6 ± 0.45[bcd]	34.3 ± 0.73[abcd]	1.21 ± 0.03[fghi]	2.76 ± 0.12[cde]	19.6 ± 0.64[cd]	21.0 ± 1.35[hi]	Oblong
CBJ0042	40.7 ± 1.82[cde]	34.2 ± 1.75[bcd]	1.19 ± 0.03[ghij]	2.71 ± 0.24[cde]	23.8 ± 3.38[bc]	25.6 ± 1.29[abcdefg]	Ovate
CBJ0043	35.2 ± 1.70[gh]	26.3 ± 1.30[hij]	1.34 ± 0.02[bcde]	2.88 ± 0.22[abcd]	11.6 ± 1.75[g]	27.9 ± 2.14[abc]	Cylindrical
CBJ0045	31.5 ± 1.79[ij]	24.3 ± 0.88[jkl]	1.30 ± 0.05[cdefg]	2.94 ± 0.10[abcd]	8.8 ± 1.00[gh]	29.4 ± 1.89[a]	Cylindrical
CBJ0046	36.6 ± 1.17[gh]	28.4 ± 2.98[fghij]	1.30 ± 0.11[cdefg]	2.80 ± 0.19[bcde]	13.5 ± 3.04[efg]	27.4 ± 0.87[abcdef]	Cylindrical
CBJ0047	34.0 ± 0.86[hi]	26.8 ± 0.78[hij]	1.27 ± 0.04[efgh]	3.34 ± 0.22[a]	11.0 ± 0.72[g]	27.5 ± 3.39[abcde]	Cylindrical
CBJ0048	36.0 ± 0.64[gh]	27.5 ± 1.76[ghij]	1.32 ± 0.10[bcdef]	3.14 ± 0.10[abc]	12.7 ± 1.49[efg]	26.8 ± 2.75[abcdefg]	Cylindrical
CBJ0052	36.9 ± 1.30[fgh]	26.4 ± 0.67[hij]	1.40 ± 0.03[bcd]	3.14 ± 0.11[abc]	11.9 ± 0.97[fg]	28.6 ± 0.56[ab]	Cylindrical
CBJ0061	37.1 ± 2.18[efgh]	26.0 ± 1.34[hijk]	1.43 ± 0.04[b]	3.04 ± 0.03[abcd]	11.4 ± 1.85[g]	28.8 ± 0.87[ab]	Cylindrical
CBJ0072	37.8 ± 1.68[efg]	34.9 ± 1.26[abcd]	1.09 ± 0.02[jklm]	2.89 ± 0.21[abcd]	20.9 ± 2.43[cd]	23.8 ± 0.54[defgh]	Oblong
CBJ0075	40.2 ± 1.52[cdef]	38.5 ± 1.43[a]	1.05 ± 0.01[klm]	2.98 ± 0.69[abcd]	26.9 ± 2.94[ab]	24.4 ± 2.04[cdefgh]	Oblong
CBJ0082	30.3 ± 0.40[jk]	29.5 ± 1.02[efgh]	1.03 ± 0.03[lm]	2.34 ± 0.22[e]	12.8 ± 0.98[efg]	26.7 ± 0.60[abcdefg]	Round
CBJ0089	45.2 ± 1.51[a]	32.2 ± 0.55[cdef]	1.41 ± 0.04[bc]	2.67 ± 0.14[cde]	19.7 ± 2.03[cd]	23.9 ± 0.81[cdefgh]	Obovate
CBJ0090	45.1 ± 0.79[ab]	33.4 ± 1.07[cde]	1.35 ± 0.03[bcde]	2.74 ± 0.19[cde]	20.0 ± 1.56[cd]	23.6 ± 0.97[efghi]	Obovate
CBJ0092	16.6 ± 0.90[m]	16.6 ± 1.56[m]	1.01 ± 0.10[m]	2.61 ± 0.39[de]	2.4 ± 0.53[i]	27.8 ± 3.44[abcd]	Round
CBJ0101	29.7 ± 1.37[jk]	29.0 ± 1.72[fghi]	1.03 ± 0.02[lm]	2.86 ± 0.21[abcd]	12.3 ± 1.98[fg]	24.9 ± 1.01[bcdefgh]	Round
CBJ0102	41.7 ± 1.51[abcd]	22.0 ± 0.71[kl]	1.90 ± 0.03[a]	2.94 ± 0.07[abcd]	9.1 ± 0.86[gh]	23.3 ± 0.63[fghi]	Conical
CBJ0103	34.0 ± 2.32[hi]	26.5 ± 1.96[hij]	1.29 ± 0.06[defg]	2.96 ± 0.13[abcd]	11.3 ± 1.04[g]	27.7 ± 1.43[abcd]	Cylindrical
CBJ0104	30.4 ± 0.97[jk]	29.1 ± 1.16[fgh]	1.04 ± 0.02[klm]	2.66 ± 0.35[cde]	12.6 ± 1.36[efg]	24.2±1.77[cdefgh]	Oblate
CBJ0109	43.6 ± 2.04[abc]	31.2 ± 1.44[defg]	1.40 ± 0.03[bcd]	3.04 ± 0.05[abcd]	17.3 ± 2.78[def]	19.5±1.48[i]	Obovate
CBJ0115	35.9 ± 2.18[gh]	28.3 ± 1.41[fghij]	1.27 ± 0.03[efgh]	3.09 ± 0.12[abcd]	12.8 ± 1.68[efg]	27.3±0.28[abcdef]	Cylindrical
CBJ0120	35.8 ± 1.93[gh]	27.2 ± 1.48[ghij]	1.32 ± 0.05[bcdef]	2.71 ± 0.46[cde]	12.4 ± 1.78[efg]	27.3±1.55[abcdef]	Cylindrical
CBJ0136	28.2 ± 0.80[jk]	27.4 ± 0.32[ghij]	1.03 ± 0.02[lm]	2.97 ± 0.06[abcd]	10.9 ± 0.41[g]	29.3±1.39[a]	Oblate
CBJ0140	23.6 ± 1.15[l]	21.3 ± 0.93[l]	1.11 ± 0.02[ijklm]	3.11 ± 0.09[abc]	5.2 ± 0.72[hi]	26.1±0.94[abcdefg]	Oblate
CBJ0144	38.2 ± 2.12[defg]	34.3 ± 6.36[abcd]	1.14 ± 0.15[ijkl]	3.12 ± 0.11[abc]	20.0 ± 6.50[cd]	25.4±0.88[abcdefg]	Cylindrical
CBJ0166	43.6 ± 1.62[abc]	37.8 ± 2.06[ab]	1.16 ± 0.04[hijk]	3.00 ± 0.23[abcd]	29.5 ± 3.38[a]	22.9±5.54[ghi]	Cylindrical

[1)]Accession No. indicates accession numbers assigned by the Jujube Research Institute. [2)]FMI, fruit morphological index (fruit length / fruit width). TSS, total soluble solids. Values are presented as mean ± SD based on tree-year means (n = 6 per accession; 3 trees per year × 2 years). Each tree-year mean was calculated from 30 fruits (subsamples) harvested at commercial maturity (≥ 70% skin coloration). Different letters within a column indicate significant differences among accessions according to Tukey's HSD test ($p < 0.05$).

differences in reported TSS values among studies may reflect seasonal conditions and harvest maturity at sampling (Jang *et al*., 2006; Lee *et al*., 2017; Lee *et al*., 2018; Oh *et al*., 2020; Park *et al*., 2023). Collectively, several accessions compared favorably with major commercial cultivars in Korea, including 'Bokjo' (Fig. 2E) and 'Hwangsil' (Fig. 2A), suggesting their potential to broaden the genetic base and support breeding programs targeting diverse market preferences (Liu *et al*., 2020; Oh *et al*., 2020; Kim *et al*., 2021a).

4. Stone traits and kernel formation rate of jujube accessions

Stone traits, particularly kernel formation, are summarized in Table 4 and Fig. 3. Quantitative stone traits (weight and size) were positively associated with fruit enlargement, consistent with previous findings (Oh *et al*., 2020). 'Gwangam' had the greatest stone weight (0.94 g), followed by 'Hwangsil' (0.87 g; Fig. 3A), whereas small-fruited accessions such as 'Sanjo' and 'Hongjinjujo' showed markedly lower stone weights (0.36 and 0.35 g, respectively). The stone morphology index (SMI)

Table 4. Stone morphological traits and kernel formation rate of 30 jujube accessions.

Accession No.[1)]	Length (mm)	Width (mm)	SMI[2)]	Weight (g)	Shape	Kernel formation rate (%)
CBJ0001	20.3 ± 0.34^{ij}	8.69 ± 0.18^{bcde}	2.35 ± 0.03^{ghij}	0.67 ± 0.02^{cdef}	Fusiform	87.4 ± 9.42^{ab}
CBJ0002	16.2 ± 0.43^{kl}	9.12 ± 0.24^{abcd}	1.79 ± 0.06^{l}	0.57 ± 0.03^{efghi}	Elliptic	98.3 ± 4.12^{a}
CBJ0025	20.9 ± 2.54^{ghi}	9.38 ± 0.75^{abc}	2.25 ± 0.18^{hijk}	0.73 ± 0.19^{bcd}	Long obovate	2.1 ± 1.12^{g}
CBJ0038	21.0 ± 1.42^{ghi}	8.15 ± 0.42^{defghi}	2.59 ± 0.14^{efg}	0.60 ± 0.07^{defghi}	Long obovate	0.0 ± 0.00^{g}
CBJ0041	26.2 ± 0.58^{bc}	9.12 ± 0.28^{abcd}	2.89 ± 0.12^{de}	0.74 ± 0.07^{bcd}	Long obovate	0.0 ± 0.00^{g}
CBJ0042	24.1 ± 1.09^{cde}	8.20 ± 0.34^{defgh}	2.95 ± 0.18^{d}	0.67 ± 0.05^{cdef}	Long obovate	0.0 ± 0.00^{g}
CBJ0043	21.9 ± 1.15^{efghi}	7.70 ± 0.30^{efghi}	2.85 ± 0.13^{de}	0.45 ± 0.06^{ijklm}	Long obovate	2.1 ± 2.04^{g}
CBJ0045	18.4 ± 1.12^{jk}	7.86 ± 0.46^{efghi}	2.36 ± 0.09^{ghi}	0.46 ± 0.08^{ijklm}	Long obovate	6.3 ± 5.10^{g}
CBJ0046	21.0 ± 0.41^{ghi}	8.43 ± 0.45^{cdefgh}	2.51 ± 0.14^{fgh}	0.54 ± 0.06^{fghijk}	Long obovate	6.4 ± 6.07^{g}
CBJ0047	20.6 ± 0.50^{hij}	7.58 ± 0.54^{hi}	2.73 ± 0.14^{def}	0.49 ± 0.15^{ghijklm}	Long obovate	4.3 ± 2.16^{g}
CBJ0048	21.4 ± 1.18^{fghi}	7.58 ± 0.30^{hi}	2.84 ± 0.14^{de}	0.47 ± 0.41^{hijklm}	Long obovate	4.2 ± 1.18^{g}
CBJ0052	23.1 ± 0.58^{defg}	7.85 ± 0.34^{efghi}	2.97 ± 0.16^{d}	0.51 ± 0.03^{ghijk}	Long obovate	13.4 ± 6.48^{fg}
CBJ0061	23.4 ± 1.10^{def}	7.77 ± 0.54^{efghi}	3.04 ± 0.10^{cd}	0.55 ± 0.13^{efghij}	Long obovate	7.3 ± 3.12^{g}
CBJ0072	21.1 ± 0.90^{ghi}	9.49 ± 0.57^{ab}	2.23 ± 0.08^{hijk}	0.75 ± 0.11^{bc}	Long obovate	0.0 ± 0.00^{g}
CBJ0075	22.7 ± 1.12^{defgh}	9.89 ± 0.93^{a}	2.35 ± 0.12^{ghij}	0.87 ± 0.12^{ab}	Long obovate	2.2 ± 2.04^{g}
CBJ0082	15.6 ± 0.29^{lm}	7.78 ± 0.25^{efghi}	2.01 ± 0.04^{jkl}	0.42 ± 0.02^{jklm}	Elliptic	86.3 ± 2.22^{ab}
CBJ0089	29.6 ± 1.66^{a}	8.15 ± 0.23^{defgh}	3.67 ± 0.30^{ab}	0.61 ± 0.03^{cdefgh}	Long obovate	7.2 ± 3.45^{g}
CBJ0090	28.8 ± 0.65^{a}	8.66 ± 0.36^{bcdef}	3.36 ± 0.14^{bc}	0.63 ± 0.04^{cdefg}	Long obovate	12.2 ± 2.22^{fg}
CBJ0092	10.8 ± 0.73^{n}	7.92 ± 0.39^{efghi}	1.37 ± 0.13^{m}	0.36 ± 0.03^{lm}	Round	99.4 ± 2.00^{a}
CBJ0101	14.9 ± 0.73^{lm}	7.69 ± 0.33^{fghi}	1.94 ± 0.12^{kl}	0.39 ± 0.04^{klm}	Elliptic	94.3 ± 10.47^{ab}
CBJ0102	25.0 ± 0.57^{cd}	6.47 ± 0.11^{j}	3.86 ± 0.10^{a}	0.41 ± 0.02^{jklm}	Fusiform	43.4 ± 9.54^{e}
CBJ0103	20.5 ± 1.34^{hij}	7.65 ± 0.65^{ghi}	2.71 ± 0.38^{def}	0.49 ± 0.08^{ghijklm}	Fusiform	87.3 ± 10.44^{ab}
CBJ0104	15.6 ± 0.39^{lm}	7.66 ± 0.30^{ghi}	2.05 ± 0.04^{ijkl}	0.40 ± 0.04^{jklm}	Elliptic	93.4± 6.22^{ab}
CBJ0109	27.9 ± 0.64^{ab}	8.34 ± 0.39^{defgh}	3.37 ± 0.11^{bc}	0.60 ± 0.03^{defghi}	Long obovate	3.2± 3.11^{g}
CBJ0115	21.1 ± 1.43^{ghi}	8.18 ± 0.22^{defgh}	2.59 ± 0.21^{efg}	0.50 ± 0.02^{ghijkl}	Long obovate	25.4± 7.43^{f}
CBJ0120	21.9± 1.53^{efghi}	8.08 ± 0.28^{efghi}	2.71 ± 0.17^{def}	0.53 ± 0.08^{fghijk}	Long obovate	49.1± 12.12^{de}
CBJ0136	16.5± 0.44^{kl}	8.60 ± 0.19^{bcdefg}	1.92 ± 0.06^{kl}	0.60 ± 0.03^{defghi}	Elliptic	83.0± 8.11^{ab}
CBJ0140	13.4± 0.76^{m}	7.16 ± 0.61^{ij}	1.88 ± 0.06^{l}	0.35 ± 0.08^{m}	Elliptic	80.1± 10.34^{bc}
CBJ0144	20.3± 1.33^{ij}	9.93 ± 0.56^{a}	2.06 ± 0.24^{ijkl}	0.69 ± 0.05^{cde}	Elliptic	64.2± 10.22^{cd}
CBJ0166	24.0± 1.21^{cde}	10.01 ± 0.71^{a}	2.42 ± 0.06^{fgh}	0.94 ± 0.09^{a}	Long obovate	0.0± 0.00^{g}

[1)]Accession No. indicates accession numbers assigned by the Jujube Research Institute. [2)]SMI, stone morphological index (length / width). Values are presented as mean ± SD based on tree-year means (n = 6 per accession; 3 trees per year × 2 years). Each tree-year mean was calculated from 30 stones (subsamples). Kernel formation rate was determined for each tree-year as the proportion of stones containing a fully developed kernel among the 30 stones evaluated for that tree-year. Different letters within a column indicate significant differences among accessions according to Tukey's HSD test ($p < 0.05$).

ranged widely, with 'Wolgwang' showing the highest SMI (3.86; Fig. 3E) and 'Sanjo' the lowest (1.37; Fig. 3C), consistent with reported diversity in stone shape among accessions (Oh *et al*., 2020; Oh *et al*., 2025b). Kernel formation differed substantially among the 30 accessions. Representative cultivars such as 'Bokjo' (25.4%; Fig. 3F), 'Cheonhwang' (2.2%), and 'Gwangam' (0.0%) showed low kernel formation rates, and their stones were frequently empty, consistent with the predominantly parthenocarpic tendency reported in cultivated jujube (Ackerman, 1961). In contrast, 'Sanjo', 'Jc-28a', and '6wolseonjo' showed high kernel formation rates of 99.4%, 98.3%, and 94.3%, respectively. These results indicate that kernel formation varies widely among jujube accessions and that high-kernel-forming accessions may be useful as potential seed-parent candidates in breeding programs (Asatryan and Tel-Zur, 2013; Oh *et al*., 2020; Oh *et al*., 2025b).

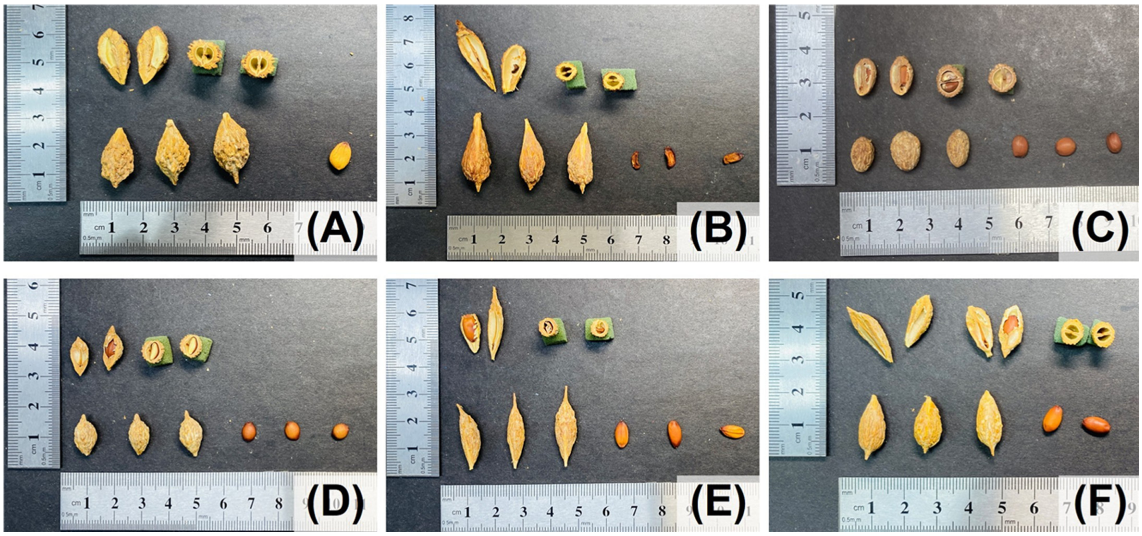

Fig. 3. Morphological characteristics of stones and kernels in selected jujube accessions. Representative stones and kernels showing variation in shape, size, and kernel filling level: (A) CBJ0075 (Hwangsil), (B) CBJ0089 (Uiseong-B), (C) CBJ0092 (Sanjo), (D) CBJ0101 (6wolseonjo), (E) CBJ0102 (Wolgwang), and (F) CBJ0115 (Bokjo). A ruler in each photograph indicates scale (cm).

5. Physicochemical characteristics of jujube juice

Results of juice pH and titratable acidity (TA), which influence perceived flavor and processing suitability, are presented in Table 5. TA (expressed as malic acid equivalents) ranged from 0.27% to 2.33% across accessions. Most accessions showed low-to-moderate acidity (generally ≤ 0.8%), whereas a few accessions exhibited higher TA values. Notably, ‘Sanjo’ showed distinctly high TA (2.33%), indicating that this accession has a markedly acidic juice profile compared with the other evaluated accessions. Juice pH ranged from 3.60 (‘Sanjo’) to 5.14 (‘Cheonsang’) and tended to decrease as TA increased, consistent with the expected pH–acidity relationship (Choi and Choi, 2023; Lee *et al*., 2025). From an application perspective, high-acidity accessions (‘Sanjo’) may be useful as blending materials for processed products, whereas low-acidity accessions may be preferable for fresh consumption where a milder acid profile is desired. Collectively, these results indicate substantial among-accession variation in acidity-related juice traits (pH and TA) (Kang *et al*., 2006; Jo *et al*., 2015; Park *et al*., 2018; Park *et al*., 2021).

6. Bioactive compounds and antioxidant activity in jujube fruits

The concentrations of vitamin C, TPC, and TFC in the fruit pulp of the 30 jujube accessions are summarized in Table 6. Vitamin C, a major antioxidant constituent in jujube fruit, varied widely across the 30 accessions (535.9–1,472.5 mg/100 g). ‘Sanjo’ showed the highest vitamin C content (1,472.5 mg/100 g), which was approximately 2.7-fold higher than that of ‘Sahongdaejo’ (535.9 mg/100 g), the lowest among the evaluated accessions. In addition, ‘Bokjo-60’ (1,006.0 mg/100 g) and ‘Wolchul-80’ (973.9 mg/100 g) also exhibited high vitamin C contents, suggesting that these accessions may serve as promising materials for breeding high-functionality cultivars. Overall, these patterns were broadly consistent with previous reports on bioactive constituents in jujube fruit (Park and Kim, 2016; Wojdyło *et al*., 2016b; Lee *et al*., 2025).

TPC, representing major secondary metabolites associated with antioxidant and anti-inflammatory effects (Kim *et al*., 2017), ranged from 523.5 to 1,325.3 mg/100 g. ‘Sanjo’ showed the highest TPC (1,325.3 mg/100 g), followed by ‘Uiseong-5’ (1,172.4 mg/100 g) and ‘Uiseong-15’ (1,140.3 mg/100 g). TFC also varied substantially among accessions: ‘Bokjo-80’ recorded the highest TFC (461.3 mg/100 g), and ‘Mudeung-60’ (334.7 mg/100 g) and ‘Sanjo’ (319.6 mg/100 g) were among the accessions with higher TFC values. The overall patterns in TPC and TFC were comparable to those reported previously (Han *et al*., 2015; Wojdyło *et al*., 2016a; Lee *et al*., 2025).

Some accessions exhibited relatively large standard deviations in the present study, which may be attributable to within-accession biological variability among trees and microenvironmental heterogeneity within the orchard, even under uniform management. In addition, although a uniform harvest criterion (≥ 70% skin coloration) was applied to all accessions,

Table 5. Juice pH and titratable acidity of 30 jujube accessions.

Accession No.[1)]	pH	Titratable acidity (%)
CBJ0001	4.98 ± 0.14[abcde]	0.28 ± 0.05[ij]
CBJ0002	4.75 ± 0.34[abcdef]	0.62 ± 0.08[bcdefghij]
CBJ0025	4.04 ± 0.18[ijk]	0.85 ± 0.16[bc]
CBJ0038	5.14 ± 0.14[a]	0.39 ± 0.15[ghij]
CBJ0041	4.65 ± 0.13[bcdefg]	0.37 ± 0.04[ghij]
CBJ0042	4.97 ± 0.19[abcde]	0.36 ± 0.07[fghij]
CBJ0043	5.06 ± 0.13[abc]	0.31 ± 0.06[ghij]
CBJ0045	4.58 ± 0.05[cdefgh]	0.46 ± 0.05[cdefghij]
CBJ0046	5.03 ± 0.16[abcd]	0.35 ± 0.02[ghij]
CBJ0047	5.00 ± 0.28[abcd]	0.28 ± 0.05[j]
CBJ0048	4.97 ± 0.17[abcde]	0.36 ± 0.06[fghij]
CBJ0052	5.07 ± 0.25[ab]	0.29 ± 0.03[hij]
CBJ0061	5.04 ± 0.12[abcd]	0.27 ± 0.02[j]
CBJ0072	4.66 ± 0.09[bcdefg]	0.47 ± 0.20[defghij]
CBJ0075	4.77 ± 0.13[abcdef]	0.36 ± 0.01[fghij]
CBJ0082	4.34 ± 0.06[fghij]	0.68 ± 0.04[bcdefg]
CBJ0089	4.37 ± 0.18[fghi]	0.63 ± 0.24[bcdefghij]
CBJ0090	4.76 ± 0.05[abcdef]	0.41 ± 0.07[efghij]
CBJ0092	3.60 ± 0.07[k]	2.33 ± 0.51[a]
CBJ0101	4.35 ± 0.19[fghi]	0.70 ± 0.20[bcdef]
CBJ0102	4.18 ± 0.15[hij]	0.75 ± 0.07[bcde]
CBJ0103	3.89 ± 0.12[jk]	0.96 ± 0.10[b]
CBJ0104	4.24 ± 0.12[ghij]	0.69 ± 0.08[bcdefg]
CBJ0109	4.49 ± 0.05[efghi]	0.66 ± 0.05[bcdefghi]
CBJ0115	5.11 ± 0.17[a]	0.36 ± 0.05[ghij]
CBJ0120	4.97 ± 0.16[abcde]	0.34 ± 0.01[ghij]
CBJ0136	4.37 ± 0.09[fghi]	0.67 ± 0.14[bcdefgh]
CBJ0140	4.13 ± 0.29[hij]	0.80 ± 0.16[bcd]
CBJ0144	4.58 ± 0.10[bcdefgh]	0.50 ± 0.07[cdefghij]
CBJ0166	4.62 ± 0.30[defg]	0.39 ± 0.18[ghij]

[1)]Accession No. indicates accession numbers assigned by the Jujube Research Institute. Values are presented as mean ± SD based on tree-year means (n = 6 per accession; 3 trees per year × 2 years). For each tree-year replicate, juice samples were prepared by pooling fruits harvested from that tree, and pH and titratable acidity were measured from the composite juice. Titratable acidity is expressed as malic acid equivalents (%). Different letters within a column indicate significant differences among accessions according to Tukey's HSD test ($p < 0.05$).

physiological maturity may not have been fully synchronized because of differences in maturity traits among accessions, which could partly contribute to variation in the accumulation of bioactive compounds. This interpretation is consistent with previous reports indicating that measured contents can vary depending on sample pretreatment and harvest timing (Kim *et al*., 2011; Choi *et al*., 2016).

To assess overall antioxidant capacity, DPPH and ABTS radical-scavenging activities were determined. In the present dataset, accessions with higher bioactive compound contents tended to show higher radical-scavenging activity. DPPH scavenging activity ranged from 13.4% to 90.3%, with 'Sanjo' showing the highest activity (90.3%). ABTS scavenging activity likewise reached its maximum in 'Sanjo' (96.6%), and 'Bokjo-60' (91.3%) also exhibited strong activity. Collectively, 'Sanjo' combined high vitamin C and TPC with correspondingly strong antioxidant activities, suggesting that it may serve as a promising resource for developing natural antioxidants and functional food materials (Kim and Joo, 2005; Oh *et al*., 2020; Lee *et al*., 2025).

To support the interpretation of the two-year pooled results, two-way ANOVA was conducted to evaluate the effects of accession, year, and accession × year interaction. Accession effects were detected for most evaluated traits, confirming substantial variation among the genetic resources. Year effects and accession × year interactions were also observed for some traits, indicating that annual variation should be considered when interpreting the pooled results. Therefore, the main tables were used to summarize overall accession-dependent differences, while the results were interpreted with caution regarding year-to-year variability.

7. Correlation analysis among traits

Correlation analysis was performed to evaluate relationships among growth traits, fruit quality attributes, and bioactive compound contents across the 30 accessions based on the two-year pooled averages; results are presented as a heatmap (Fig. 4). ABTS radical-scavenging activity showed strong positive correlations with vitamin C content (r = 0.80, $p < 0.001$) and DPPH activity (r = 0.90, $p < 0.001$), indicating that variation in antioxidant activity was closely aligned with vitamin C levels in this dataset. In comparison, total phenolic content (TPC; r = 0.27, *ns*) and total flavonoid content (TFC; r = 0.32, *ns*) exhibited relatively weak associations with ABTS activity, suggesting that vitamin C contributed more strongly to the observed variation in radical-scavenging capacity among these accessions (Gao *et al*., 2012).

Fruit weight showed a significant negative correlation with TSS (r = −0.56, $p < 0.01$), consistent with the trade-off between fruit size and sweetness reported in other fruit crops

Table 6. Antioxidant activities and bioactive compound contents in the fruit pulp of 30 jujube accessions.

Accession No.[1)]	Antioxidant activities (%)		Vitamin C (mg ascorbic acid / 100 g DW)	Total phenolic content (TPC, mg GAE / 100 g DW)	Total flavonoid content (TFC, mg QE / 100 g DW)
	DPPH radical scavenging	ABTS radical scavenging			
CBJ0001	39.4 ± 3.75^{ghij}	65.8 ± 2.26^{cdefg}	873.8 ± 88.62^{bcdef}	640.0 ± 292.55^{efg}	90.9 ± 11.12^{efghi}
CBJ0002	58.6 ± 5.50^{bcd}	71.0 ± 2.10^{cdef}	950.8 ± 56.66^{bcde}	1071.2 ± 127.51^{abcd}	131.3 ± 49.68^{efghi}
CBJ0025	41.2 ± 1.17^{efghij}	58.0 ± 2.43^{efghij}	626.0 ± 46.02^{efg}	743.9 ± 32.06^{cdefg}	202.5 ± 57.69^{bcdefgh}
CBJ0038	25.6 ± 2.97^{klmno}	63.3 ± 7.40^{defgh}	749.3 ± 59.34^{bcdefg}	1003.5 ± 129.16^{abcde}	309.1 ± 74.56^{abcd}
CBJ0041	13.4 ± 2.89^{p}	52.8 ± 3.23^{ghij}	679.7 ± 184.97^{bcdefg}	967.4 ± 232.73^{abcdef}	252.1 ± 51.71^{bcde}
CBJ0042	40.2 ± 3.48^{fghij}	68.1 ± 3.58^{cdefg}	779.3 ± 102.05^{bcdefg}	1029.2 ± 48.78^{abcde}	178.9 ± 57.13^{bcdefghi}
CBJ0043	53.8 ± 5.83^{cde}	80.3 ± 3.60^{abc}	964.9 ± 109.06^{bcd}	1174.1 ± 36.99^{ab}	334.7 ± 110.26^{ab}
CBJ0045	29.9 ± 2.61^{jklmn}	55.2 ± 2.20^{ghij}	814.2 ± 13.26^{bcdefg}	1044.6 ± 102.45^{abcde}	123.4 ± 26.15^{efghi}
CBJ0046	45.9 ± 2.91^{defgh}	72.6 ± 2.65^{cde}	973.9 ± 151.00^{bc}	737.1 ± 276.07^{cdefg}	165.4 ± 181.21^{cdefghi}
CBJ0047	67.7 ± 3.01^{b}	91.3 ± 4.52^{ab}	1006.0 ± 96.31^{b}	551.6 ± 30.13^{fg}	31.2 ± 2.67^{i}
CBJ0048	52.7 ± 11.94^{cdef}	77.1 ± 11.61^{bcd}	849.5 ± 30.70^{bcdefg}	967.3 ± 102.05^{abcdef}	461.3 ± 85.57^{a}
CBJ0052	36.0 ± 5.28^{hijk}	67.1 ± 3.20^{cdefg}	776.4 ± 19.25^{bcdefg}	1172.4 ± 50.88^{ab}	180.0 ± 7.52^{bcdefghi}
CBJ0061	31.1 ± 1.40^{ijklmn}	64.6 ± 3.65^{cdefgh}	835.0 ± 8.88^{bcdefg}	1140.3 ± 47.73^{abc}	129.1 ± 8.44^{efghi}
CBJ0072	22.2 ± 6.54^{nop}	50.7 ± 10.53^{hij}	537.1 ± 162.98^{g}	523.5 ± 95.16^{g}	37.2 ± 12.13^{i}
CBJ0075	18.2 ± 6.69^{op}	47.3 ± 6.31^{ij}	636.1 ± 61.93^{defg}	867.8 ± 195.51^{bcdefg}	171.8 ± 124.14^{bcdefghi}
CBJ0082	34.3 ± 1.70^{hijkl}	61.3 ± 4.92^{defghi}	828.4 ± 108.07^{bcdefg}	1090.1 ± 103.84^{abcd}	131.4 ± 54.94^{efghi}
CBJ0089	33.6 ± 1.24^{hijklmn}	55.4 ± 2.53^{fghij}	636.9 ± 73.93^{defg}	775.3 ± 140.86^{bcdefg}	57.8 ± 25.20^{hi}
CBJ0090	41.0 ± 3.86^{fghij}	63.2 ± 1.47^{defgh}	777.3 ± 59.45^{bcdefg}	677.1 ± 22.94^{defg}	82.3 ± 33.77^{fghi}
CBJ0092	90.3 ± 6.03^{a}	96.6 ± 1.74^{a}	1472.5 ± 181.34^{a}	1325.3 ± 164.06^{a}	319.6 ± 41.40^{abc}
CBJ0101	33.9 ± 2.34^{hijklm}	57.6 ± 2.92^{efghij}	883.4 ± 344.43^{bcde}	846.3 ± 184.26^{bcdefg}	128.1 ± 33.22^{efghi}
CBJ0102	42.7 ± 1.29^{efghi}	60.1 ± 1.73^{efghij}	677.3 ± 26.51^{bcdefg}	744.9 ± 281.78^{cdefg}	63.40 ± 42.33^{ghi}
CBJ0103	66.9 ± 9.46^{b}	76.1 ± 7.39^{bcd}	978.8 ± 224.83^{bc}	974.6 ± 70.97^{abcde}	214.8 ± 19.11^{bcdefgh}
CBJ0104	30.4 ± 1.80^{ijklmn}	59.5 ± 2.72^{efghij}	721.3 ± 18.36^{bcdefg}	790.1 ± 202.13^{bcdefg}	115.3 ± 17.53^{efghi}
CBJ0109	44.7 ± 3.82^{efgh}	66.1 ± 6.82^{cdefg}	757.1 ± 66.27^{bcdefg}	826.8 ± 156.27^{bcdefg}	105.1 ± 65.48^{efghi}
CBJ0115	24.2 ± 4.32^{lmno}	61.4 ± 10.37^{efgh}	823.8 ± 146.54^{bcdefg}	971.9 ± 217.58^{abcde}	162.4 ± 49.13^{defghi}
CBJ0120	36.1 ± 2.95^{hijk}	62.7 ± 6.56^{defgh}	830.2 ± 118.68^{bcdefg}	973.4 ± 117.28^{abcde}	104.3 ± 5.62^{efghi}
CBJ0136	40.0 ± 3.34^{fghij}	59.5 ± 7.11^{efghij}	691.1 ± 26.97^{bcdefg}	890.5 ± 133.48^{bcdefg}	124.6 ± 12.80^{efghi}
CBJ0140	60.9 ± 2.17^{bc}	72.6 ± 2.90^{cde}	647.7 ± 176.67^{cdefg}	856.6 ± 185.00^{bcdefg}	188.7 ± 46.62^{bcdefghi}
CBJ0144	49.1 ± 3.44^{cdefg}	65.9 ± 1.93^{cdefg}	535.9 ± 43.78^{g}	754.6 ± 29.21^{bcdefg}	238.5 ± 34.36^{bcdef}
CBJ0166	21.2 ± 0.47^{mnop}	44.2 ± 6.54^{j}	548.7 ± 34.57^{fg}	877.0 ± 104.02^{bcdefg}	223.7 ± 58.03^{bcdefg}

[1)]Accession No. indicates accession numbers assigned by the Jujube Research Institute. Values are presented as mean ± SD based on tree-year replicates (n = 6 per accession; 3 trees per year × 2 years). For each tree-year replicate, pulp samples were prepared from fruits harvested at commercial maturity (≥ 70% skin coloration) and analyzed as an independent biological replicate. Vitamin C is expressed as mg ascorbic acid per 100 g dry weight (DW), TPC as mg gallic acid equivalents (GAE) per 100 g DW, and TFC as mg quercetin equivalents (QE) per 100 g DW. DPPH and ABTS activities are expressed as radical-scavenging activity (%). Different letters within a column indicate significant differences among accessions according to Tukey's HSD test (p < 0.05).

such as peach (Buendía *et al*., 2008). Furthermore, fruit weight was strongly negatively correlated with functional attributes, including vitamin C (r = –0.64, p < 0.001), DPPH activity (r = –0.61, p < 0.001), and ABTS activity (r = –0.63, p < 0.001). This indicates a negative association between fruit enlargement and antioxidant-related traits in the present dataset. This suggests that simultaneous improvement of fruit size, sweetness, and functional quality may require careful selection of parental combinations to mitigate these negative associations.

Furthermore, kernel formation rate was positively correlated

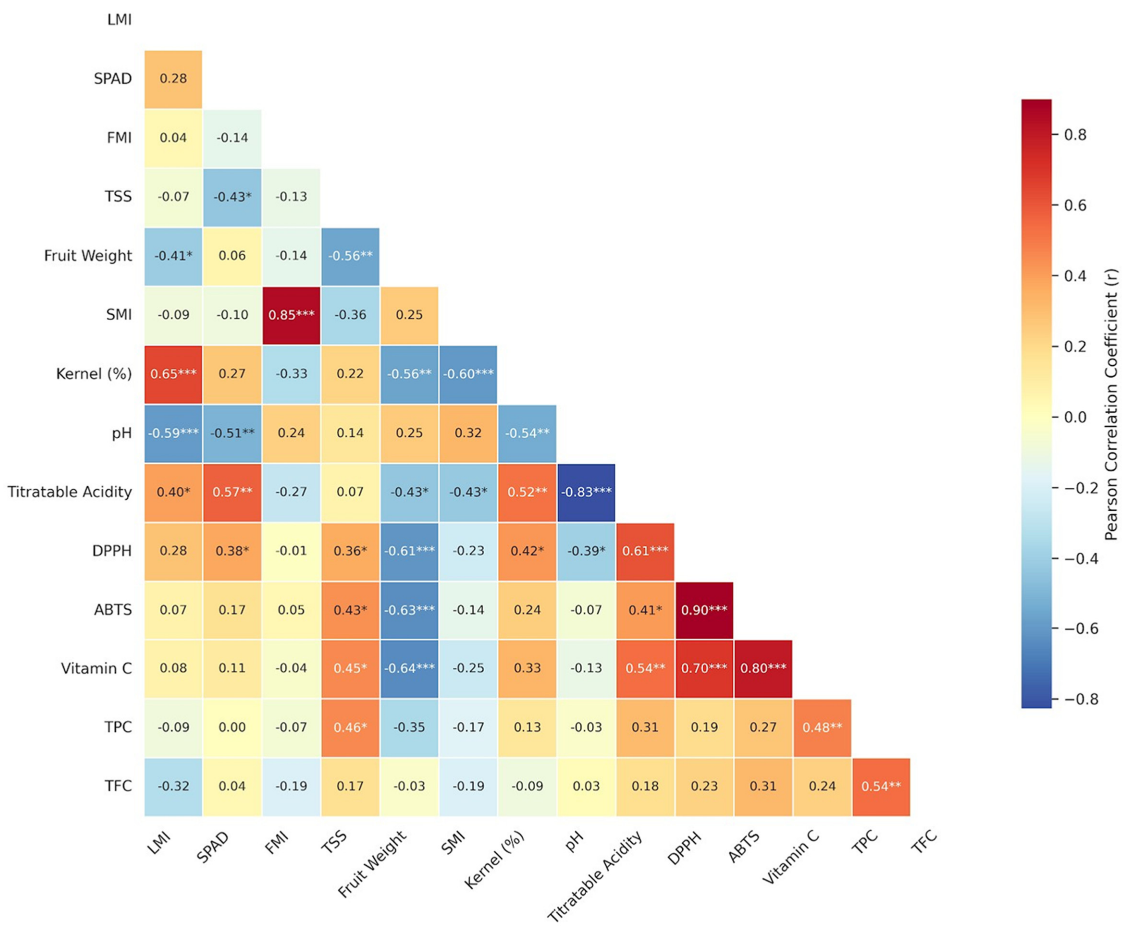

Fig. 4. Heatmap of Pearson's correlation coefficients among physicochemical traits, bioactive compounds, and morphological traits in 30 jujube accessions. Positive and negative correlations are represented in red and blue, respectively, and color intensity corresponds to the absolute magnitude of the correlation coefficient. Correlation coefficients were calculated across 30 accessions (n = 30). *, **, and *** indicate significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

with the leaf morphology index (LMI; r = 0.65, p < 0.001), titratable acidity (r = 0.52, p < 0.01), and DPPH activity (r = 0.42, p < 0.05). In contrast, kernel formation rate was negatively correlated with fruit weight (r = –0.56, p < 0.01), the stone morphology index (SMI; r = –0.60, p < 0.001), and pH (r = –0.54, p < 0.01). These correlations indicate that accessions with higher kernel formation, such as 'Sanjo', tended to show narrower leaves, smaller fruits, and a more acidic juice profile (Oh *et al*., 2025b). Overall, these findings suggest that breeding for high-functionality cultivars may benefit from prioritizing accessions with high vitamin C content and favorable seed traits as potential seed parents, while selecting pollen parents with a balanced combination of fruit weight and TSS to improve sweetness without substantially reducing fruit size (Oh *et al*., 2020).

CONCLUSION

This study evaluated the potential of 30 jujube accessions preserved in Korea as breeding resources by comparing fruit morphological traits, physicochemical properties, and bioactive compound profiles over two consecutive years (2022–2023). The evaluated accessions exhibited substantial variation in key traits, including fruit size, total soluble solids (TSS), titratable acidity, and bioactive compound contents, indicating considerable potential for breeding material selection.

Marked accession-dependent differences were observed in major market-related traits. In particular, 'Wolchul-60' showed the highest TSS (29.4 °Brix), whereas 'Gwangam' produced the largest fruit (29.5 g), highlighting their potential as parental materials for improving sweetness and fruit size, respectively. Bioactive compound analyses also revealed pronounced diversity among accessions. Notably, 'Sanjo' recorded the highest vitamin C content (1,472.5 mg ascorbic acid/100 g DW) and total phenolic content (TPC; 1,325.3 mg GAE/100 g DW), and exhibited the strongest DPPH and ABTS radical-scavenging activities, suggesting its potential as a valuable resource for developing jujube cultivars and functional products with enhanced bioactive properties.

Correlation analysis indicated that antioxidant capacity was closely associated with vitamin C content across the evaluated accessions, suggesting that vitamin C may be a useful selection trait for improving functional quality in jujube breeding. Fruit weight was negatively associated with antioxidant-related traits, indicating that simultaneous improvement of fruit size and bioactive compound accumulation may require careful selection of parental combinations. In addition, kernel formation rate was positively associated with the leaf morphology index, titratable acidity, and antioxidant-related traits, but negatively associated with fruit weight and pH. These results suggest that high-kernel-forming accessions may provide useful variation for breeding, particularly in relation to acidity, fruit size, and antioxidant-related traits.

Collectively, the high-TSS accession 'Wolchul-60', the large-fruited accession 'Gwangam', and the vitamin C- and TPC-rich accession 'Sanjo' represent promising breeding resources for developing new jujube cultivars and high-value functional products that meet diverse consumer demands.

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