

Nutritional profile of *Pyrus pyrifolia* (Burm.f.) Nakai: organ-specific variation

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Abstract

Pyrus pyrifolia (Burm.f.) Nakai is an economically important fruit species widely cultivated in Asia and increasingly recognized as a source of valuable nutrients and bioactive compounds. Despite its growing utilization, comprehensive information on organ-specific variability of its biochemical composition remains limited. This study investigates the nutritional profile (proximate, β -carotene, amino acids, fatty acids, minerals, and vitamins) of different organs of *P. pyrifolia* (leaves, seeds, pulp, and fruit peel) using standard biochemical analytical methods. The results revealed significant organ-specific variation in nutritional composition. Seeds were characterized by the highest dry matter (90.40%), protein (22.60%), and fat (26.80%) concentrations, with oleic acid being the dominant fatty acid (48.90 g/100 g of fat) and a high concentration of monounsaturated fatty acids (50.10 g/100 g of fat). Fruit pulp showed the highest concentrations of carbohydrates, particularly fructose (72.50 g/kg) and sucrose (38.60 g/kg). Leaves exhibited the highest ash (10.30%), β -carotene (38.50 mg/kg), vitamin E (72.40 mg/kg), and polyunsaturated fatty acids (41.20 g/100 g of fat), as well as the greatest concentrations of potassium (18,500 mg/kg) and calcium (12,400 mg/kg). The seeds contained a notable level of phosphorus (3,800 mg/kg). All samples showed low levels of potentially toxic elements, confirming the safety of the samples. PCA and HCA clearly distinguished the organs into separate clusters based on their nutritional profiles, highlighting distinct compositional patterns among leaves, seeds, pulp, and peel. These findings highlight the potential of *Pyrus pyrifolia* as a promising resource for human nutrition and the development of functional food ingredients and natural food additives.

Keywords: *Pyrus pyrifolia* (Burm.f.) Nakai, Nutritional potential, Mineral elements, Fatty acids, Biochemical composition, Multivariate analysis

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Introduction

Species of the genus *Pyrus* L. (Rosaceae Juss.) constitute significant dietary resources, providing easily digestible carbohydrates, organic acids, and essential mineral elements, as well as a wide range of biologically active compounds, including phenolics and antioxidants^[1–3]. Regular consumption of fruits and plant-derived products is widely recognized as an important factor in the prevention of chronic non-communicable diseases, largely due to the antioxidant and metabolic activities of phytochemicals^[4,5].

Particular attention has recently been given to the Asian pear, *Pyrus pyrifolia* (Burm.f.) Nakai, a species widely cultivated in East Asia and increasingly introduced in Europe as a promising fruit crop^[6,7]. Its fruit is appreciated for its high juiciness, crisp texture, and elevated content of soluble sugars, all of which contribute to consumer preference and commercial value^[8,9]. In modern food biochemistry and applied biotechnology, increasing attention is being paid not only to fruit as food products but also to vegetative plant organs, which are often underutilized^[1,10,11].

A promising approach is the valorization of secondary plant materials such as leaves, peel, and seeds to produce functional ingredients and natural antioxidants^[12,13]. In many fruit crops, phenolic compounds and antioxidants are predominantly concentrated in

the peel, while the pulp mainly functions as a reservoir for sugars and water^[14,15]. Additionally, leaves of woody plants are valuable sources of polyphenols, pigments, and minerals, as demonstrated by studies evaluating their bioactive properties^[15–18]. Fruit seeds also deserve attention. Although traditionally regarded as processing waste, seeds are specialized structures for the storage of proteins and lipids^[19–21]. Seed oils of many fruit crops are rich in unsaturated fatty acids, particularly oleic and linoleic acids, which have high nutritional value^[22,23] and are recommended by the FAO/WHO for balanced dietary fat intake^[24]. Seeds of *P. pyrifolia* have been identified as promising sources of lipids and bioactive compounds, including phenolics, sterols, and tocopherols^[22]. However, comparative information on the nutritional composition of different plant organs remains limited.

Despite the increasing interest in Asian pear as a functional food resource, comprehensive nutritional characterization of its different organs is still scarce. Most available studies focus mainly on fruit^[19–21,25–27], whereas leaves, seeds, and peel remain insufficiently investigated. The nutritional composition, including amino acid profile, fatty acid composition, sugars, vitamins, and mineral elements, may provide valuable information for the practical utilization of these organs in food, pharmaceutical, and biotechnological applications.

In this context, the aim of this study was to characterize the biochemical composition of leaves, seeds, pulp, and peel of *P. pyrifolia* (Burm.f.) Nakai with emphasis on amino acid profile, fatty acid composition, sugar content, vitamins, and mineral elements, and to evaluate their potential as sources of functional ingredients.

Materials and methods

Chemicals and reagents

All chemicals and reagents used in this study were of analytical or HPLC grade. Acetonitrile, methanol, ethanol, n-hexane, petroleum ether, acetone, sodium hydroxide (NaOH), boron trifluoride–methanol complex (BF₃–methanol), potassium hydroxide (KOH), nitric acid (HNO₃), anhydrous sodium sulphate, and sodium-citrate buffers were purchased from Sigma-Aldrich (Steinheim, Germany) and Merck (Darmstadt, Germany). Ultrapure water was obtained using a Milli-Q purification system. Certified standards of sugars (fructose, maltose, sucrose, lactose), amino acids, fatty acid methyl esters (Supelco 37 Component FAME Mix), retinol acetate, and α -tocopherol acetate were obtained from Sigma-Aldrich (Steinheim, Germany). Multi-element calibration standards for ICP-OES analysis were purchased from Merck (Darmstadt, Germany). Additional laboratory reagents were supplied by CentralChem (Bratislava, Slovakia).

Plant material

Leaves, seeds, fruit pulp, and peel of *P. pyrifolia* (Fig. 1) were harvested from mature trees cultivated at the MM Gryshko National Botanical Garden of the National Academy of Sciences of Ukraine (Kyiv, Ukraine; 50°24'53" N, 30°33'42" E; 197 m above sea level). The region is characterized by a temperate continental climate with an average annual temperature of approximately 7.4–7.7 °C and annual precipitation of 550–650 mm. Samples were randomly collected from five healthy trees at the stage of physiological fruit maturity during the 2024 growing season. Immediately after harvest, the plant material was transported to the laboratory and separated into individual organs (leaves, seeds, pulp, and peel). All samples were washed with distilled water, air-dried, and subsequently dried in a forced-air drying oven at 45 °C until constant weight was achieved. The dried material was milled into a fine homogeneous powder using a laboratory grinder (IKA A11 basic, Germany) and stored

in airtight containers at room temperature until analysis. All biochemical analyses were performed on a dry weight basis. Prior to analysis, the powdered samples were thoroughly homogenized to ensure sample uniformity.

Nutritional analyses

Proximate composition analysis

Dry matter, ash, and crude protein contents were determined according to the AACC^[28] method 08-01. Nitrogen content was measured using the semi-micro Kjeldahl method, and crude protein content was calculated using a nitrogen conversion factor of 6.25.

Fat content was determined using an Ancom XT15 fat extractor (Ancom, USA) following the manufacturer's instructions. Briefly, 1.5 g of sample (W1) was placed into a filter bag (XT4, Ancom, USA) and dried at 105 °C for 3 h to remove moisture. The bag was cooled in a desiccator and weighed (W2), then extracted with petroleum ether for 60 min at 90 °C. After extraction, the sample was dried again at 105 °C for 30 min, cooled in a desiccator, and reweighed (W3).

The fat content percentage was subsequently calculated using the following equation: $[(W2 - W3)/W1] \times 100$.

Sugar content

For the determination of sugar content, 1 g of sample was vigorously shaken with 10 mL of a water/ethanol mixture (4:1, v/v) on a vertical shake table (GFL, Germany). After 1 h of extraction, the mixture was centrifuged at $3,330 \times g$ for 4 min (EBA 21, Hettich, Germany). The supernatant was filtered through 0.45 μ m filter paper (Labicom, Czech Republic) and diluted to 50 mL with ultrapure water in a volumetric flask. Sugar analysis (fructose, maltose, sucrose, and lactose) was performed using High-Performance Liquid Chromatography (HPLC) on an Agilent Infinity 1260 system (Agilent Technologies, USA) equipped with an evaporative light scattering detector (ELSD). Separation was carried out using a Prevail Carbohydrates ES column (250 $\times$ 4.6 mm). The mobile phase consisted of acetonitrile/water (75:25, v/v) delivered at a flow rate of 1.0 mL/min. The column temperature was maintained at 30 °C, and the injection volume was 20 μ L. ELSD detector settings were adjusted to a drift tube temperature of 40 °C and a nitrogen gas flow rate of 1.5 L/min. The total chromatographic run time was 20 min. Identification of sugars was achieved by comparing the relative retention times of sample peaks with certified reference standards (Sigma-Aldrich, Steinheim, Germany). Sugar contents were expressed as g/kg dry weight^[29].

Determination of vitamin A and vitamin E

Vitamin A and vitamin E were determined using the same High-Performance Liquid Chromatography (HPLC) system described above (Agilent Infinity 1260, USA) following solvent extraction. Approximately 1 g of dried and homogenized sample was mixed with 10 mL ethanol and subjected to saponification with ethanolic potassium hydroxide solution, when required for matrix clarification, under controlled conditions. Vitamins were subsequently extracted with n-hexane. The organic phase was collected, evaporated under reduced pressure, and the residue was re-dissolved in a known volume of mobile phase prior to chromatographic analysis. Separation was performed on a reversed-phase C18 column under isocratic conditions. The mobile phase consisted of a methanol/water mixture optimized for vitamin separation at a flow rate of 1.0 mL/min. The column temperature was maintained at 30 °C, and the injection volume was 20 μ L. Detection wavelengths were set at 325 nm for vitamin A (retinol acetate) and 292 nm for vitamin E (α -tocopherol acetate) using a UV-Vis detector.

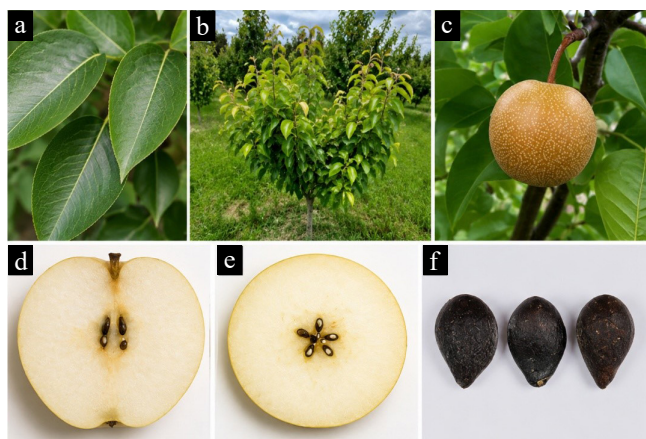


Fig. 1 Morphological characteristics and analyzed organs of *P. pyrifolia*: (a) leaves; (b) tree; (c) fruit; (d) fruit pulp in longitudinal section; (e) fruit pulp in transverse section; and (f) seeds (photo: Goncharovska). Scale bars: (a) 5 cm; (b) 50 cm; (c)–(e) 2 cm; (f) 1 cm.

Identification was based on comparison of retention times with certified reference standards (Sigma-Aldrich). Quantification was achieved using external calibration curves. Vitamin contents were expressed as mg/kg dry weight^[30].

β-carotene content

A 0.5 g sample was homogenized in a mortar with sea sand (2 g) and repeatedly extracted with 10 mL of acetone until the sample became colourless. Each extraction was performed for 10 min, and the extraction procedure was repeated three times. The extract was filtered through Whatman filter paper and used for the determination of total carotenoid content. A separating funnel with a Teflon stopcock containing 20 mL of petroleum ether was used. The acetone extract and distilled water were added carefully along the walls of the funnel. The mixture was allowed to separate into two phases for 1 min, after which the aqueous phase was discarded. The petroleum ether phase was washed twice with distilled water to remove residual acetone. The petroleum ether phase was collected in a 50 mL volumetric flask by passing the solution through a small funnel containing 5 g of anhydrous sodium sulphate to remove residual water. The volumetric flask was then made up to volume with petroleum ether, and the total carotenoid content was determined using the molar absorption coefficient of β-carotene^[31,32].

The concentration (mg/g) of β-carotene was calculated according to the following formula:

$$\beta\text{-carotene [mg/g]} = \frac{A \cdot r \cdot V \cdot 10}{E \cdot n}$$

where: *A* is absorbance at 445 nm; *r* is sample dilution; *V* is volume of petroleum ether phase; *E* is molar absorption coefficient *E* = 2,620; and *n* is sample weight.

Mineral content analyses

Mineral and trace metallic elements were determined using inductively coupled plasma optical emission spectroscopy (ICP-OES; Thermo iCAP Dual 6500, USA). Approximately 0.2 g of each powdered sample was subjected to microwave-assisted digestion (Ethos One, Milestone, Italy) in Teflon vessels containing 8 mL of 65% HNO₃. The digestion protocol lasted 1 h with a temperature ramp not exceeding 200 °C. Each digested sample was diluted to a final volume of 50 mL with ultrapure water, and a blank sample (acid only) was processed in parallel. Calibration was performed using certified standard solutions (Merck): 10,000 mg/L for Ca, Fe, K, Mg, and P, and 1,000 mg/L for Na, Al, Ba, Cu, Ni, Mn, Sr, Se, Pb, Hg, As, Cd, S, and Zn. A three-point calibration curve was prepared for each element. Internal standard correction using yttrium and ytterbium ions (2–5 mg/L) was applied to minimize instrumental drift^[33].

Amino acid analysis

The amino acid composition was determined using an amino acid analyzer (Ingos, Prague, Czech Republic) based on ion-exchange chromatography with a strong cation-exchange resin and a sodium-citrate buffer system. Post-column derivatization with ninhydrin and spectrophotometric detection were used for amino acid quantification. The instrument was calibrated using standard amino acid solutions. Tryptophan was not determined because it is degraded during acid hydrolysis. Asparagine and glutamine were quantified as aspartic acid and glutamic acid, respectively, due to deamidation during hydrolysis.

Fatty acid analysis

Preparation of fatty acid methyl esters (FAMES)

A 0.1 g oil sample (previously isolated from the samples by petroleum ether extraction during the fat extraction procedure) was

transferred into a 40 mL glass vial and mixed with 5 mL of 0.50 M methanolic NaOH. The mixture was heated at 60 °C for 3 min and subsequently cooled to room temperature. Then, 6 mL of a 14% boron trifluoride–methanol complex (BF₃) was added, and the mixture was reheated at 60 °C for an additional 3 min. After cooling, 10 mL of isooctane was added. The mixture was vigorously shaken and allowed to separate into phases. The upper organic phase containing FAMES was collected and passed through anhydrous sodium sulphate to remove residual moisture. Prior to chromatographic analysis, the esterified oil samples were diluted in n-hexane at a ratio of 1:19 (50 μL FAME + 950 μL n-hexane).

Chromatographic analysis (GC/FID)

Fatty acid methyl esters (FAMES) were analysed qualitatively and quantitatively using an Agilent 7890B gas chromatograph equipped with a flame ionisation detector (FID). Sample injection was performed using a CombiPAL autosampler (Agilent Technologies, Santa Clara, CA, USA), with an injection volume of 1 μL. Chromatographic separation was achieved using an HP-88 capillary GC column (60 m × 0.25 mm i.d. × 0.20 μm film thickness). The oven temperature programme was as follows: initial temperature 120 °C held for 1 min; increased at 10 °C/min to 175 °C and held for 10 min; increased at 5 °C/min to 210 °C and held for 5 min; and finally increased at 5 °C/min to 230 °C and held for 10 min. The injector temperature was maintained at 250 °C and the FID temperature at 260 °C. Helium (He, 5.0 purity) was used as the carrier gas at a constant flow rate of 1 mL/min with a split ratio of 50:1. Hydrogen was supplied to the FID at 40 mL/min, synthetic air at 450 mL/min, and nitrogen (N₂) as makeup gas at 25 mL/min. Data acquisition and processing were carried out using Agilent OpenLab ChemStation software (LTS 01.11). Calibration was performed using a Supelco 37-component FAME mix containing certified reference materials (CRM; TraceCERT, Supelco, USA). Identification of individual FAMES was confirmed by retention time comparison and characteristic mass spectral ions using an Agilent 5977A MSD system (Agilent Technologies, Santa Clara, CA, USA)^[34].

Statistical analysis

All measurements were performed in triplicate, and the results are expressed as mean ± standard deviation (SD). Statistical analysis was carried out to evaluate differences among the organs of *P. pyrifolia* (leaves, seeds, pulp, and peel). One-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post hoc test was applied to determine statistically significant differences between mean values at *p* < 0.05. Different superscript letters in the tables indicate significant differences among the analysed organs. Pearson's correlation coefficient (*r*) was used to assess relationships between selected biochemical and mineral parameters. Principal component analysis (PCA) and hierarchical cluster analysis (HCA) were performed using standardized data to evaluate multivariate relationships among variables and plant organs. All statistical analyses were conducted using XLSTAT v2024.1 (Addinsoft, Paris, France) integrated with Microsoft Excel.

Results

Proximate composition

The proximate composition of different organs of *P. pyrifolia* is presented in Table 1. Considerable differences in the contents of biochemical compounds were observed among the analysed plant organs. Seeds were characterised by the highest dry matter, protein, and fat contents, indicating their role as a storage organ rich in

reserve substances. In contrast, the pulp contained the lowest dry matter and protein contents and only trace amounts of lipids. Leaves showed relatively high protein and ash contents, suggesting their potential as a nutritionally valuable plant material and reflecting intensive mineral accumulation. The peel exhibited intermediate values for most analysed parameters.

Sugar content

The sugar concentrations in different organs of *P. pyrifolia* are summarised in Table 1. The pulp was identified as the main site of carbohydrate accumulation, with fructose and sucrose representing the predominant sugars. The peel also contained considerable concentrations of these sugars, although at lower levels compared to the pulp. In contrast, leaves and seeds were characterised by substantially lower sugar concentrations. Maltose was detected mainly in the pulp, while lactose was not detected in any analysed sample, which is typical for plant-derived materials. The distribution of sugars among the organs reflects their different physiological functions and involvement in fruit metabolism^[8].

β -carotene content

The β -carotene content (Table 1) differed markedly among the analysed organs of *P. pyrifolia*. Leaves were the richest source of β -carotene, followed by the peel, whereas the pulp contained only low concentrations of this compound. The elevated β -carotene content in leaves is associated with their photosynthetic function and the presence of chloroplast pigments^[2].

Vitamin A and E content

Vitamin A (retinol acetate) was detected in low concentrations in all analysed organs of *P. pyrifolia* (Table 1). The highest vitamin A content was observed in leaves, whereas lower concentrations were found in the peel, seeds, and pulp. In contrast, vitamin E (α -tocopherol acetate) was detected at substantially higher concentrations, with leaves and seeds representing the richest sources of this vitamin. The pulp contained the lowest concentrations of both analysed vitamins.

Table 1. Content of nutritional profile in different organs of *P. pyrifolia* (Burm.f.) Nakai.

Component	Leaves	Seed	Pulp	Peel
Dry matter (%)	35.2 $\pm$ 2.5 ^b	90.4 $\pm$ 4.0 ^a	13.6 $\pm$ 1.2 ^c	20.1 $\pm$ 1.5 ^c
Protein (%)	14.8 $\pm$ 1.2 ^b	22.6 $\pm$ 1.5 ^a	4.2 $\pm$ 0.4 ^c	7.5 $\pm$ 0.6 ^c
Ash (%)	10.3 $\pm$ 0.8 ^a	4.1 $\pm$ 0.5 ^b	2.4 $\pm$ 0.3 ^c	5.2 $\pm$ 0.5 ^b
Fat (%)	4.2 $\pm$ 0.4 ^b	26.8 $\pm$ 2.0 ^a	0.50 $\pm$ 0.05 ^c	1.6 $\pm$ 0.2 ^c
Fructose (g/kg)	18.4 $\pm$ 1.6 ^b	6.2 $\pm$ 0.7 ^c	72.5 $\pm$ 5.0 ^a	34.1 $\pm$ 3.0 ^b
Maltose (g/kg)	6.3 $\pm$ 0.6 ^b	3.1 $\pm$ 0.3 ^c	12.4 $\pm$ 1.0 ^a	8.2 $\pm$ 0.8 ^b
Sucrose (g/kg)	14.8 $\pm$ 1.5 ^b	5.4 $\pm$ 0.5 ^c	38.6 $\pm$ 3.0 ^a	22.3 $\pm$ 2.0 ^b
β -Carotene (g/kg)	0.06 $\pm$ 0.01 ^a	0.04 $\pm$ 0.001 ^b	0.02 $\pm$ 0.003 ^c	0.05 $\pm$ 0.01 ^{ab}
Vitamin A (retinol acetate) (g/kg)	72.4 $\pm$ 5.5 ^a	64.8 $\pm$ 4.5 ^a	6.9 $\pm$ 0.7 ^c	15.3 $\pm$ 1.5 ^b
Vitamin E (α -tocopherol acetate) (g/kg)	20.4 $\pm$ 1.8 ^b	14.2 $\pm$ 1.2 ^c	27.6 $\pm$ 2.0 ^a	22.3 $\pm$ 1.9 ^b
Saturated fatty acids (g/100 g)	30.6 $\pm$ 2.5 ^b	50.1 $\pm$ 4.0 ^a	35.2 $\pm$ 3.0 ^b	40.5 $\pm$ 3.2 ^{ab}
Monounsaturated fatty acids (g/100 g)	41.2 $\pm$ 3.5 ^a	30.4 $\pm$ 2.8 ^b	31.8 $\pm$ 2.5 ^b	29.1 $\pm$ 2.5 ^b
Polyunsaturated fatty acids (g/100 g)	35.2 $\pm$ 2.5 ^b	90.4 $\pm$ 4.0 ^a	13.6 $\pm$ 1.2 ^c	20.1 $\pm$ 1.5 ^c

Values are presented as mean $\pm$ standard deviation ($n = 3$). Different letters within the same column indicate statistically significant differences among mean values according to Tukey's test ($p < 0.05$).

Amino acid content

The amino acid composition of the analysed organs of *P. pyrifolia* is presented in Table 2. Seeds were characterised by the highest concentrations of most amino acids, indicating their role as the primary protein storage organ. Leaves also contained considerable amino acid concentrations, particularly acidic amino acids, whereas the pulp and peel showed substantially lower amino acid contents. Essential amino acids were predominantly detected in seeds and leaves, while their concentrations in the fruit tissues were markedly lower.

Fatty acid content

The fatty acid composition of the analysed organs of *P. pyrifolia* is presented in Table 3. Saturated fatty acids (SFA) were represented mainly by palmitic acid (C16:0), which predominated in the pulp and peel. In contrast, seeds were characterised by lower SFA proportions and the highest concentrations of monounsaturated fatty acids (MUFA), mainly due to the predominance of oleic acid (C18:1). Leaves, pulp, and peel also contained considerable amounts of oleic acid, although at lower levels than seeds. Among polyunsaturated fatty acids (PUFA), linoleic (C18:2) and α -linolenic (C18:3) acids were the dominant compounds. Leaves were characterised by the highest PUFA proportion, particularly because of their elevated α -linolenic acid content, indicating their potential as a source of ω -3 fatty acids. Overall, the fatty acid distribution differed markedly among the analysed organs, reflecting their distinct physiological and storage functions.

Mineral and trace metallic element content

The mineral composition of the analysed organs of *P. pyrifolia* is presented in Table 4. Leaves were characterised by the highest concentrations of major mineral elements, particularly potassium, calcium, magnesium, and iron, indicating their important role in mineral accumulation. In contrast, seeds contained the highest phosphorus concentrations, reflecting their storage function. The pulp generally showed the lowest concentrations of most macro- and microelements. Trace metallic elements, including As, Cd, Hg, and Pb, were detected at low concentrations in all analysed organs. Among these elements, leaves tended to accumulate higher

Table 2. Amino acid composition in different organs of *P. pyrifolia* (Burm.f.) Nakai.

Component (g/kg)	Leaves	Seed	Pulp	Peel
Alanine	8.20 $\pm$ 0.8 ^a	15.40 $\pm$ 1.3 ^b	2.10 $\pm$ 0.3 ^c	4.30 $\pm$ 0.3 ^c
Arginine	9.80 $\pm$ 1.0 ^a	28.60 $\pm$ 2.8 ^b	1.90 $\pm$ 0.1 ^c	5.10 $\pm$ 0.3 ^c
Glycine	7.10 $\pm$ 0.7 ^a	12.30 $\pm$ 1.1 ^b	1.50 $\pm$ 0.1 ^c	3.60 $\pm$ 0.2 ^c
Histidine	3.90 $\pm$ 0.3 ^a	6.80 $\pm$ 0.8 ^b	0.90 $\pm$ 0.06 ^c	2.10 $\pm$ 0.05 ^c
Isoleucine	5.40 $\pm$ 0.4 ^a	9.70 $\pm$ 0.8 ^b	1.20 $\pm$ 0.1 ^c	2.80 $\pm$ 0.06 ^c
Glutamic acid	21.50 $\pm$ 2.0 ^a	42.10 $\pm$ 3.1 ^b	6.30 $\pm$ 0.4 ^c	11.40 $\pm$ 1.7 ^c
Leucine	9.20 $\pm$ 0.6 ^a	16.80 $\pm$ 1.6 ^b	2.40 $\pm$ 0.01 ^c	5.20 $\pm$ 0.3 ^c
Lysine	8.60 $\pm$ 0.9 ^a	14.20 $\pm$ 1.2 ^b	1.80 $\pm$ 0.02 ^c	4.10 $\pm$ 0.3 ^c
Phenylalanine	6.30 $\pm$ 0.5 ^a	11.50 $\pm$ 0.7 ^b	1.40 $\pm$ 0.02 ^c	3.20 $\pm$ 0.2 ^c
Proline	10.40 $\pm$ 1.1 ^a	18.90 $\pm$ 1.4 ^b	3.10 $\pm$ 0.2 ^c	6.80 $\pm$ 0.3 ^c
Serine	6.80 $\pm$ 0.5 ^a	13.20 $\pm$ 1.2 ^b	1.70 $\pm$ 0.04 ^c	3.90 $\pm$ 0.3 ^c
Threonine	5.10 $\pm$ 0.4 ^a	9.40 $\pm$ 0.6 ^b	1.30 $\pm$ 0.01 ^c	2.90 $\pm$ 0.2 ^c
Tyrosine	4.60 $\pm$ 0.4 ^a	8.30 $\pm$ 0.4 ^b	1.10 $\pm$ 0.06 ^c	2.60 $\pm$ 0.2 ^c
Total	106.90	187.30	28.80	58.00

Values are presented as mean $\pm$ standard deviation ($n = 3$). Different letters within the same column indicate statistically significant differences among mean values according to Tukey's test ($p < 0.05$).

Table 3. Fatty acid composition in different organs of *P. pyrifolia* (Burm.f.) Nakai.

Fatty acid (g/100 g)	Leaves	Seed	Pulp	Peel
Caprylic acid C8:0	0.20 ± 0.01 ^a	0.10 ± 0.001 ^b	0.30 ± 0.02 ^a	0.20 ± 0.01 ^a
Capric acid C10:0	0.30 ± 0.02 ^a	0.20 ± 0.01 ^b	0.40 ± 0.02 ^a	0.30 ± 0.01 ^a
Lauric acid C12:0	0.60 ± 0.03 ^a	0.40 ± 0.02 ^b	0.80 ± 0.04 ^a	0.50 ± 0.03 ^a
Myristic acid C14:0	1.20 ± 0.08 ^a	0.90 ± 0.05 ^b	1.50 ± 0.05 ^a	1.10 ± 0.04 ^a
Palmitic acid C16:0	15.40 ± 1.12 ^a	9.80 ± 0.65 ^b	18.20 ± 1.17 ^a	16.10 ± 0.37 ^a
Heptadecanoic acid C17:0	0.40 ± 0.02 ^a	0.30 ± 0.01 ^b	0.50 ± 0.03 ^a	0.40 ± 0.01 ^a
Stearic acid C18:0	4.60 ± 0.21 ^a	3.20 ± 0.12 ^b	5.10 ± 0.36 ^a	4.80 ± 0.18 ^a
Arachidic acid C20:0	0.80 ± 0.04 ^a	0.60 ± 0.02 ^b	0.90 ± 0.05 ^a	0.70 ± 0.04 ^{ab}
Behenic acid C22:0	0.60 ± 0.04 ^a	0.50 ± 0.02 ^b	0.70 ± 0.04 ^a	0.60 ± 0.02 ^a
Lignoceric acid C24:0	0.50 ± 0.02 ^a	0.40 ± 0.03 ^b	0.60 ± 0.03 ^a	0.50 ± 0.02 ^a
SFAs	24.6	16.4	29.0	25.2
Palmitoleic acid C16:1	3.10 ± 0.19 ^a	2.60 ± 0.19 ^b	3.80 ± 0.22 ^a	3.40 ± 0.21 ^{ab}
Oleic acid C18:1	29.80 ± 2.15 ^a	48.90 ± 3.34 ^b	32.40 ± 2.11 ^a	36.20 ± 2.12 ^a
Tetracosenoic acid C24:1	0.70 ± 0.06 ^a	0.60 ± 0.02 ^{ab}	0.80 ± 0.03 ^a	0.70 ± 0.04 ^a
Eicosenoic acid C20:1	1.10 ± 0.09 ^a	0.90 ± 0.05 ^b	1.20 ± 0.02 ^a	1.00 ± 0.07 ^{ab}
Erucic acid C22:1	0.90 ± 0.04 ^a	0.70 ± 0.03 ^b	1.00 ± 0.05 ^a	0.80 ± 0.05 ^{ab}
MUFAs	36.4	54.3	40.1	42.9
Linoleic acid C18:2	23.60 ± 2.14 ^a	26.40 ± 2.23 ^a	21.30 ± 1.10 ^b	20.10 ± 1.04 ^b
Linolenic acid C18:3	12.40 ± 1.07 ^a	5.80 ± 0.46 ^c	10.20 ± 1.01 ^b	8.90 ± 0.54 ^b
Arachidonic acid C20:4	0.40 ± 0.02 ^a	0.30 ± 0.02 ^b	0.50 ± 0.03 ^a	0.40 ± 0.02 ^a
PUFAs	36.4	32.5	32.0	29.4

Values are presented as mean ± standard deviation ($n = 3$); SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids. Different letters within the same column indicate statistically significant differences among mean values according to Tukey's test ($p < 0.05$).

Table 4. Mineral compound composition in different organs of *P. pyrifolia* (Burm.f.) Nakai.

Mineral compound (mg/kg)	Leaves	Seed	Pulp	Peel
Macroelements				
P	2,100 ± 150 ^a	3,800 ± 250 ^b	120 ± 15 ^c	420 ± 40 ^c
K	18,500 ± 1200 ^a	7,200 ± 500 ^b	1450 ± 120 ^c	3,200 ± 250 ^b
Ca	12,400 ± 1000 ^a	1,200 ± 150 ^c	90 ± 10 ^c	680 ± 60 ^b
S	1,600 ± 120 ^a	2,300 ± 180 ^b	110 ± 12 ^c	350 ± 30 ^b
Mg	3,200 ± 250 ^a	1,900 ± 200 ^b	75 ± 10 ^c	420 ± 35 ^b
Na	180 ± 20 ^a	65 ± 8 ^b	12 ± 2 ^c	95 ± 10 ^b
Microelements				
Fe	210 ± 25.0 ^a	95 ± 12 ^b	6.5 ± 1.0 ^c	48 ± 6 ^b
Mn	85 ± 10.0 ^a	22 ± 3.0 ^b	1.8 ± 0.3 ^c	14 ± 2.0 ^b
Al	320 ± 40.0 ^a	110 ± 15.0 ^b	8.0 ± 1.0 ^c	75 ± 8.0 ^b
Cr	1.20 ± 0.15 ^a	0.60 ± 0.08 ^b	0.05 ± 0.01 ^c	0.40 ± 0.05 ^b
Cu	9.50 ± 1.2 ^a	6.80 ± 0.8 ^b	0.70 ± 0.08 ^c	3.20 ± 0.35 ^b
Zn	42 ± 5.0 ^b	58 ± 6.0 ^a	1.10 ± 0.12 ^c	9.80 ± 1.2 ^b
Se	0.35 ± 0.05 ^a	0.28 ± 0.03 ^b	0.03 ± 0.005 ^c	0.12 ± 0.02 ^b
As	0.18 ± 0.03 ^a	0.12 ± 0.02 ^b	0.01 ± 0.002 ^c	0.06 ± 0.01 ^b
Cd	0.06 ± 0.01 ^a	0.04 ± 0.005 ^b	0.005 ± 0.001 ^c	0.02 ± 0.004 ^b
Ni	1.80 ± 0.20 ^a	0.95 ± 0.12 ^b	0.08 ± 0.01 ^c	0.60 ± 0.08 ^b
Hg	0.010 ± 0.002 ^a	0.008 ± 0.001 ^{ab}	0.001 ± 0.0002 ^c	0.004 ± 0.0005 ^b
Pb	0.22 ± 0.03 ^a	0.16 ± 0.02 ^b	0.02 ± 0.004 ^c	0.09 ± 0.01 ^b

Values are presented as mean ± standard deviation ($n = 3$). Different letters within the same column indicate statistically significant differences among mean values according to Tukey's test ($p < 0.05$).

concentrations compared to the fruit tissues, whereas the pulp contained the lowest levels^[11].

Correlation analysis

A Pearson correlation analysis of the studied parameters revealed significant relationships among the biochemical constituents of *P.*

pyrifolia. A significant positive correlation was observed between dry matter and fat content ($r = 0.98$), indicating that organs with higher dry matter, particularly seeds, also contained higher lipid levels, whereas pulp showed the lowest values of both parameters. A similarly significant positive relationship was found between fat and protein contents ($r = 0.98$), reflecting the co-accumulation of storage compounds in seed tissues. A positive association was also detected between β -carotene and mineral (ash) content ($r = 0.94$), suggesting that photosynthetically active organs, particularly leaves, are characterised by both high carotenoid and mineral levels. In contrast, a significant negative correlation was observed between dry matter and β -carotene ($r = -0.82$), reflecting the low carotenoid content in storage tissues such as seeds. The amino acid profile showed strong positive inter-correlations among individual amino acids, indicating coordinated accumulation patterns. For example, high correlations were observed between leucine and valine ($r = 0.99$), lysine and threonine ($r = 0.98$), and valine and threonine ($r = 0.98$). Glutamic acid and aspartic acid exhibited the highest absolute concentrations across all organs, particularly in seeds. In contrast, pulp consistently showed markedly lower amino acid levels compared to other organs. Fatty acid composition also showed distinct correlation patterns. Oleic acid (C18:1) was strongly associated with total monounsaturated fatty acids (MUFA) ($r = 0.99$), while palmitic acid (C16:0) correlated with total saturated fatty acids (SFA) ($r = 0.98$). Linoleic (C18:2) and linolenic (C18:3) acids showed strong positive relationships with total polyunsaturated fatty acids (PUFA) ($r = 0.95$ – 0.98). Overall, seeds were characterised by a higher proportion of MUFA and PUFA, whereas fruit tissues exhibited relatively higher SFA levels.

Principal component analysis (PCA)

Principal component analysis (PCA) was performed on standardized biochemical variables, including dry matter, proteins, fats, ash, β -carotene, sugars, and fatty acid groups (SFA, MUFA, PUFA). The first two principal components explained 96.6% of the total variance (PC1 = 56.9%, PC2 = 39.7%) (Fig. 2). PC1 was mainly positively

associated with dry matter, protein, fat, MUFA, and total amino acids, whereas it was negatively associated with sugars. This axis clearly separated seeds from the other organs, reflecting their high content of storage compounds, particularly lipids and proteins. PC2 was primarily associated with ash content, mineral elements (Ca, K, Fe, Mn), and β -carotene, distinguishing leaves from fruit tissues. Leaves were positioned at high positive PC2 values, reflecting their enrichment in minerals and carotenoids. Based on PCA distribution, three biochemical groups of variables and corresponding organ associations were identified: Group 1 (storage-related compounds): dry matter, proteins, fats, MUFA, amino acids, strongly associated with seeds; Group 2 (photosynthetic/metabolic compounds): β -carotene, ash, Ca, K, Fe, Mn, associated with leaves; and Group 3 (carbohydrate-related compounds): sugars (fructose, sucrose), and SFA associated with pulp and peel. The PCA score plot (Fig. 2) showed clear separation of organs: seeds formed an isolated cluster, leaves were separated along PC2, while pulp and peel were closely grouped, indicating similar biochemical composition.

Hierarchical cluster analysis (HCA) (Fig. 3) based on Euclidean distance further confirmed the PCA results. The dendrogram revealed a clear separation of samples into distinct clusters: seeds formed a separate cluster, while leaves were grouped apart from fruit tissues. Pulp and peel clustered closely together, indicating their similar biochemical profiles. This clustering pattern supports the multivariate structure observed in the PCA score plot.

Discussion

The present study provides a comprehensive evaluation of the biochemical composition of *Pyrus pyrifolia*, revealing clear organ-specific differences in the distribution of nutrients and bioactive compounds. The results demonstrated that seeds are characterized by markedly higher levels of dry matter, proteins, and lipids compared with other plant organs, while leaves are enriched in mineral elements and antioxidant compounds such as β -carotene and vitamin E. These findings indicate a clear functional specialization of tissues, reflecting their distinct physiological roles in plant metabolism, storage, and protection. A comprehensive

evaluation of the biochemical composition of *P. pyrifolia* demonstrated pronounced organ-specific differentiation of nutrients and bioactive compounds. Such metabolic specialization between vegetative and generative organs is characteristic of fruit crops and reflects the physiological roles of tissues in plant growth and reproduction. Similar distribution patterns have been reported for other members of the Rosaceae family, including *Malus domestica* and *Pyrus communis*, where seeds function as storage organs rich in lipids and proteins, while leaves accumulate minerals and antioxidant compounds involved in metabolic and protective processes^[22,23,35–38]. Studies on pear physiology have also shown that fruit tissues differ significantly in biochemical composition due to their specialized roles in metabolism and reproduction^[8,39]. The results of the present study showed that the seeds of *P. pyrifolia* contained the highest levels of dry matter (90.40%), protein (22.60%), and lipids (26.80%), indicating their role as the primary storage organ of the fruit. Comparable observations have been reported for seeds of several fruit species, where high concentrations of proteins and oils ensure energy supply during germination and early seedling development^[40,41]. Previous studies on pear seeds have also demonstrated their significant nutritional potential due to the presence of essential amino acids and valuable fatty acids^[22,21]. The relatively high protein concentration observed in the seeds in this study is consistent with findings for other fruit kernels such as apple, apricot, and peach seeds, which are increasingly considered potential sources of plant-based protein ingredients for food and nutraceutical applications^[4,41]. In addition, studies by Wani et al.^[21] reported that pear seed proteins contain a balanced amino acid profile comparable to other plant protein sources, supporting their potential nutritional value.

Attention should be paid to the lipid fraction of *P. pyrifolia* seeds, which was characterized by a predominance of oleic acid (48.90 g/100 g fat). Oleic acid is a monounsaturated fatty acid widely recognized for its beneficial effects on human health, particularly its ability to reduce low-density lipoprotein cholesterol and support cardiovascular function^[42,43]. Similar fatty acid profiles have been reported for seeds of other fruit crops and oil-bearing plants, where oleic acid contributes to the oxidative stability and nutritional value of the oil^[40,41]. Research on pear and apple seed oils has also shown that oleic and linoleic acids are typically the dominant fatty acids, contributing to both nutritional quality and oxidative stability^[22,38]. Therefore, the relatively high proportion of monounsaturated fatty acids observed in this study suggests that *P. pyrifolia* seeds may represent a promising alternative source of plant oil suitable for functional food formulations and nutraceutical applications.

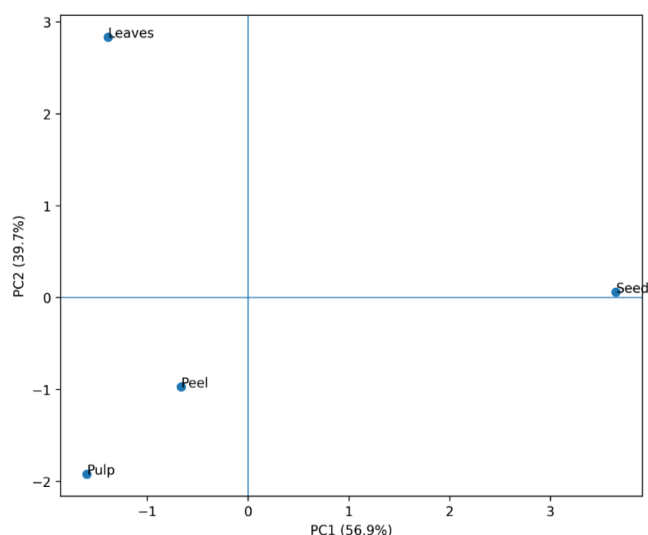


Fig. 2 Principal component analysis (PCA) of different organs of *P. pyrifolia* (Burm.f.) Nakai.

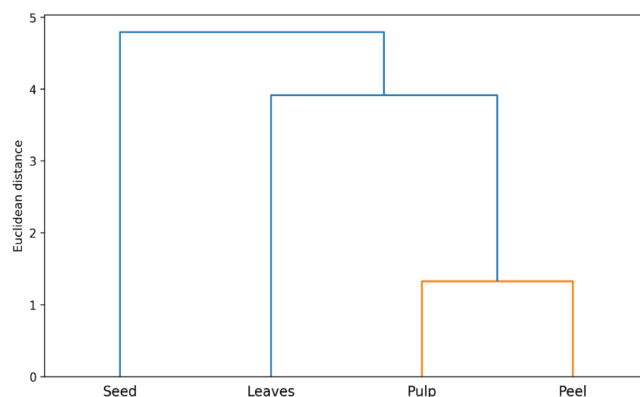


Fig. 3 Hierarchical cluster analysis (HCA) of different organs of *P. pyrifolia* (Burm.f.) Nakai.

In contrast to seeds, the leaves of *P. pyrifolia* demonstrated the highest concentrations of mineral elements and antioxidant-related compounds, including β -carotene and vitamin E. Leaves accumulated up to 38.50 mg/kg of β -carotene and 72.40 mg/kg of α -tocopherol, indicating their important physiological role in protecting photosynthetic tissues from oxidative damage. High levels of carotenoids and tocopherols in leaf tissues are commonly reported for fruit trees and are associated with photoprotection and regulation of reactive oxygen species during photosynthesis^[44]. Similar findings have been reported for pear and apple leaves, which contain significant amounts of antioxidant compounds with potential health-promoting properties^[16,38]. Carotenoids such as β -carotene play an important role in photosynthetic systems by protecting chloroplasts from photooxidative stress, which explains their high concentration in metabolically active leaf tissues^[45].

The fatty acid composition of leaves was characterized by the highest proportion of polyunsaturated fatty acids, particularly α -linolenic acid (12.40 g/100 g fat). This fatty acid belongs to the ω -3 family and is well known for its anti-inflammatory and cardioprotective properties in human nutrition^[46]. The relatively high concentration of α -linolenic acid in leaf tissues is consistent with previous reports indicating that plant leaves represent an important source of ω -3 fatty acids in terrestrial ecosystems^[2,41]. These results suggest that *Pyrus pyrifolia* leaves may have potential applications as a raw material to produce antioxidant extracts and functional ingredients.

Mineral composition analysis revealed that leaves contained the highest concentrations of potassium, calcium, magnesium, and iron. These elements play essential roles in plant metabolism, including enzyme activation, photosynthesis, and osmotic regulation. Similar trends have been reported in other fruit trees, where leaves act as the main reservoir of mineral nutrients due to their active involvement in physiological processes^[47,48]. Studies on pear trees have also demonstrated that leaf tissues accumulate higher concentrations of potassium and calcium compared with fruit tissues, reflecting their role in maintaining metabolic activity and supporting nutrient transport^[39]. In contrast, seeds accumulated the highest levels of phosphorus and zinc. The accumulation of phosphorus in seeds is physiologically justified, as it is a key component of phytate complexes that serve as storage forms of phosphorus during germination^[48].

As expected, fruit pulp served as the primary reservoir of soluble carbohydrates. Fructose (72.50 g/kg) and sucrose (38.60 g/kg) were the dominant sugars, confirming that pulp represents the main energy-providing component of the fruit. The predominance of fructose in pear fruit has been widely reported and is considered a major determinant of sweetness and consumer acceptance^[8,36]. Similar sugar profiles have been observed in Asian pear cultivars, where fructose and sorbitol are the principal soluble carbohydrates contributing to flavor and sensory quality^[22,39]. These findings confirm that the sugar composition obtained in the present study is consistent with previously reported biochemical characteristics of pear fruits.

The fruit peel also contained considerable concentrations of sugars and carotenoids, indicating that it fulfils both protective and metabolic functions. Previous studies have shown that fruit peels often accumulate higher levels of bioactive compounds, including phenolics, pigments, and antioxidants, compared with the edible pulp^[49,50]. For instance, Sun et al.^[50] reported that pear peel may contain several times higher concentrations of phenolic compounds than pulp, significantly contributing to its antioxidant activity. This suggests that peel, which is often discarded during processing, may represent a valuable source of natural pigments and antioxidant

compounds. In the context of sustainable food production, such by-products could be utilized for the development of functional ingredients, natural colorants, or dietary supplements^[5,41].

Another important finding of this study is the relatively low concentration of potentially toxic elements (As, Cd, Hg, and Pb) across all analyzed plant organs. The detected values were significantly below the maximum permissible limits established by international food safety regulations. This indicates that the investigated plant material is environmentally safe and suitable for potential applications in the food and pharmaceutical industries. Similar observations have been reported in studies evaluating heavy metal accumulation in fruit crops grown under controlled agricultural conditions^[39,47].

The multivariate statistical analysis confirmed clear biochemical differences among plant organs. Cluster analysis and principal component analysis separated seeds, leaves, and fruit tissues according to their composition. Seeds were mainly associated with higher lipid and protein contents, leaves with elevated mineral and antioxidant levels, while pulp and peel were related to carbohydrate accumulation. These results are consistent with previous studies showing that multivariate methods effectively distinguish plant organs based on their metabolic profiles^[26,44]. *P. pyrifolia* may represent a multifunctional resource with potential for integrated utilization. The pulp could serve as a carbohydrate-rich food product, seeds as a source of oil and protein, leaves as a source of antioxidant and mineral extracts, and peel as a source of bioactive compounds. Such an approach may contribute to waste reduction and better use of agricultural biomass^[5,41].

Future research could focus on phenolic content, flavonoid profiles, and antioxidant activity, which would provide a more complete characterization of the bioactive potential of *P. pyrifolia* organs^[22,50]. Further studies could also assess the bioavailability and biological activity of the identified compounds to support potential nutraceutical applications.

Conclusions

This study demonstrated clear organ-specific biochemical specialization in *P. pyrifolia*, highlighting distinct functional roles of seeds, leaves, pulp, and peel. Seeds represent a promising source of protein and lipid-rich ingredients suitable for the development of value-added food products and plant-based functional oils. Leaves show strong potential as a raw material for innovative bioactive extracts rich in antioxidants, minerals, and ω -3 fatty acids, applicable in nutraceuticals and functional foods with added health benefits. The pulp constitutes a natural carbohydrate-rich fraction with direct use in food formulations, while the peel represents an underutilized byproduct that could be valorised as a source of natural pigments, bioactive compounds, and functional additives for clean-label and sustainable food innovations. The consistently low levels of toxic elements confirm the safety and suitability of all plant fractions for further processing. Overall, the findings support the development of integrated zero-waste processing strategies and the creation of innovative high-value food and nutraceutical products from *P. pyrifolia* biomass within the framework of a circular bioeconomy.

Ethical statements

Not applicable.

Author contributions

The authors confirm their contributions to this study as follows: writing – review and editing, visualization, validation: Ivanišová E, Osei ED, Afoakwah NA; supervision, project administration: Ivanišová E, Grygorieva O; methodology and data curation: Goncharovska I, Kuznetsov V, Portia SM; software: Kuznetsov V, Kolesárová A; validation: Grygorieva O, Kolesárová A; writing – original draft, visualization, investigation, formal analysis: Goncharovska I; methodology, funding acquisition, conceptualization: Ivanišová E; writing – review and editing, investigation: Grygorieva O. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The data generated during this study are included in the published article, and further inquiries can be directed to the corresponding author.

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Conflict of interest

The authors declare no conflict of interest.

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