



Evaluation of bioactive compounds in peels of different citrus species

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ABSTRACT

Citrus fruits are valued globally for their sensory appeal and economic importance and also for their rich repository of health-promoting phytochemicals. While the edible pulp is extensively studied, citrus peel often discarded as waste, possesses a complex profile of nutritionally and functionally important compounds. Hence, the present study was aimed to assess the phytochemical diversity and functional potential of citrus peels from 14 genotypes, including both commercially cultivated and region-specific types such as Cleopatra mandarin, Troyer citrange, Satkora and Karna khatta. Different citrus fruits were collected from various agro-climatic zones across India and physio-chemical analysis was conducted in the laboratory during 2023–2025 at the Institute of Agriculture, Visva-Bharati, Sriniketan, West Bengal. Quantitative analyses revealed wide variability in key parameters including total phenolics (6.97–19.93 mg GAE/g DW), flavonoids (4.14–12.58 mg QE/g DW), ascorbic acid (72.3–156.0 mg/100 g FW), carotenoid content (67.3–306.1 µg/g FW) and DPPH radical scavenging activity (47.8–79.3%). Proximate traits such as crude fibre, protein, ash, fat, pectin and essential oil content also varied significantly, indicating species-specific biochemical signatures. Pomelo, Grapefruit and Satkora emerged as superior sources of antioxidants (79.3, 72.6 and 70.4%), while Mandarin orange and lemon showed higher pectin (28.4 and 26.5% DW) and fibre content (10.5 and 9.1% DW). Correlation analysis exhibited strong positive association among phenolics, flavonoids, vitamin C and antioxidant activity, confirming their synergistic roles. These findings support the valorisation of citrus peel as a sustainable bio-resource in food, pharmaceutical and cosmetic industries. The research also fills a critical research gap in comparative phytochemistry of citrus peels in India and underlines their potential in circular bioeconomy and functional product development.

Keywords: Citrus genotypes, Functional products, Phytochemical potential, Rind

Citrus fruits are among the most economically significant and widely cultivated fruit crops globally, known for their refreshing flavour and sensory appeal as well as exceptional nutritional value (Richa *et al.* 2023, Deb *et al.* 2025). These fruits belong to the family Rutaceae and encompass a diverse group of species, including sweet orange, mandarin, lemon, lime, grapefruit and pomelo. In India, citrus cultivation spans to a wide range of agro-climatic regions, making the country a leading producer of citrus fruits (Deb *et al.* 2024). Beyond the commonly grown varieties, India also harbours region-specific cultivars such as Cleopatra mandarin [*Citrus reshni* (Engl.) Yu Tanaka], Karna khatta (*Citrus karna* Raf.), Satkora (*Citrus macroptera*) and Troyer citrange [*Citrus sinensis* (L.) Osbeck 'Washington Navel' × *Poncirus trifoliata* L.], each with distinct physical and bio-chemical traits (Mahawar *et al.* 2025). While citrus fruits are mainly eaten for their juice or

fresh pulp, the peel, which constitutes a significant portion of the fruit biomass is often treated as a by-product or waste (Ademosun 2022, Sharma *et al.* 2022). However, scientific evidence increasingly navigates to the peel as an important source of bioactive compounds that offers numerous health and wellness benefits and industrial applications (Suri *et al.* 2021, Kumar *et al.* 2025, Negrea *et al.* 2025).

The peel of citrus fruits contains a complex matrix of phytochemicals and nutrients that far surpass the pulp in certain aspects (Nieto *et al.* 2021). These include phenolic compounds (both free and bound forms), flavonoids, vitamin C (ascorbic acid), crude dietary fiber, essential oils, pectins, proteins and different minerals (Venkataraman 2024). These constituents contribute towards wide range of biological activities, such as antioxidant, anti-inflammatory, antimicrobial, cardioprotective and even skin-enhancing effects (Goyal and Chauhan 2025). In industrial settings, citrus peels are being explored for their role in producing nutraceuticals, natural food preservatives, biodegradable materials and cosmetic products (Suri *et al.* 2022, Wedamulla *et al.* 2022). Despite these known benefits, most of the research has largely thrusted on the juice or

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edible portion of citrus fruits (Kim *et al.* 2023, Miao *et al.* 2025). Comprehensive studies analysing and comparing the nutrient and phytonutrient composition of peels across various citrus species are relatively scarce and only on few types like lemon, lime, sweet orange and pomelo on the basis of quantification of minerals and identification of phytochemicals (Prakash *et al.* 2025), particularly available in the Indian context. This underlines a significant research gap, especially given the potential of underutilised citrus species whose peel composition remains largely uncharacterised. With the growing global interest in natural antioxidants and plant-based ingredients, evaluating the peel of multiple citrus types offers an opportunity to promote value-addition and sustainable waste management in citrus processing industries.

To address this gap, the present study was designed to investigate and compare the biochemical composition and functional attributes of peels from 14 different citrus species cultivated across India including some underutilised citrus species like Troyer citrange or Karna khatta etc. The study focused on several key parameters that reflect both nutritional quality and potential industrial value. The primary objectives were to quantify the phytonutrients and nutritional properties of citrus peels across species, identify high-value genotypes suitable for valorisation and provide foundational data to support the development of natural health products and functional foods. By showcasing the prospects of citrus peels as a resource rather than waste, the research contributes toward the goals of sustainable agriculture, circular economy practices and the amplification of rural bio-industrial prospects.

MATERIALS AND METHODS

The present study was carried out during 2023–24 and 2024–25 at the Institute of Agriculture, Visva-Bharati, Sriniketan, West Bengal. Citrus fruits representing 14 distinct species, both commercially cultivated and region-specific were collected from different agro-climatic locations of India to capture genetic and environmental diversity (Fig. 1). The selected species included Mandarin orange (*Citrus reticulata* Blanco) from Darjeeling district of West Bengal, Cleopatra mandarin [*Citrus reshni* (Engl.) Yu Tanaka] from ICAR-Indian Agricultural Research Institute, New Delhi; Rangpur lime (*Citrus limonia* Osbeck) from Garo Hill of Meghalaya; Troyer citrange [*Citrus sinensis* (L.) Osbeck 'Washington Navel' × *Poncirus trifoliata* L.] from ICAR-Indian Agricultural Research Institute, New Delhi; Rough lemon (*Citrus jambhiri* Lush) from Cooch Behar district of West Bengal; Sour orange (*Citrus aurantium* L.) from Bhubaneswar, Odisha; Sweet orange (*Citrus sinensis* L.) from Bankura district of West Bengal; Satkora (*Citrus macroptera* Montrouz) from Eastern Tripura, Karnakhatta (*Citrus karna* Raf.) from ICAR-Indian Agricultural Research Institute, New Delhi, Citron (*Citrus medica* L.) from Uttar Banga Krishi Vishwavidyalaya, Cooch Behar district, West Bengal; Lime [*Citrus aurantifolia* (Christm.) Swingle] from Birbhum district of West Bengal; Lemon [*Citrus limon* (L.)

Osbeck] from Jalpaiguri district of West Bengal; Grapefruit (*Citrus paradisi* Macfad.) from ICAR-Indian Agricultural Research Institute, New Delhi and Pomelo [*Citrus maxima* (Burm) Merr.] from Dhubri district of Assam. Freshly harvested fruits at uniform physiological maturity were carefully brought to laboratory, washed, peeled manually and the peels were dried under shade followed by cabinet drier. Dried samples were ground to a powder using a laboratory blender, packed in airtight containers and kept at 4°C till further analysis (Pathan *et al.* 2010).

A series of biochemical assays have been done to quantify the phytonutrients and nutritional composition of the citrus peels. Total phenolic content (TPC) was determined by extracting both free and bound phenolics using 80% methanol and alkaline hydrolysis methods, respectively, followed by Folin-Ciocalteu reagent as reported by Chen *et al.* (2015). The absorbance has been taken at 765 nm using a UV-visible spectrophotometer and results were calculated in mg GAE (gallic acid equivalents)/g dry weight (DW). Total flavonoid content (TFC) was estimated using the aluminum chloride colorimetric assay and values were expressed as mg quercetin equivalents (QE)/g DW following the protocol described by Chang *et al.* (2002). Ascorbic acid content has been quantified by titrating the sample extract against 2,6-dichlorophenolindophenol dye, as per the method of Shishehbore and Aghamiri (2014) and expressed in mg/100 g fresh weight (FW). Carotenoid content in citrus peel was determined spectrophotometrically using acetone extraction and absorbance measurement at 450 nm, with the method described by Lichtenthaler and Wellburn (1983). Antioxidant activity was measured using DPPH radical scavenging assay, following the procedure of Brand-Williams *et al.* (1995), with slight modifications. The percentage inhibition of the DPPH radical was calculated by measuring absorbance at 517 nm and the results were interpreted as a percentage in free radical scavenging efficiency.

In addition to antioxidant and phytochemical parameters, several proximate components were analysed to measure the nutritional potential of the citrus peels. Crude fibre content were quantified by sequential acid and alkali digestion using the standard method outlined by the Association of Official Analytical Chemists (A O A C 2005) and results were manifested as percentage of dry weight. Protein content was determined using the Kjeldahl method, involving digestion followed by distillation and titration steps, with nitrogen conversion factor 6.25 for estimation of crude protein content (A O A C 2005). Ash content was determined by incinerating a known quantity of sample at 550°C under muffle furnace until a white residue was obtained and expressed as % DW (A O A C 2005). Crude fat content was determined using a Soxhlet apparatus with petroleum ether as solvent and recorded as a percentage of DW (Pearson 1976). Essential oil content has been determined using hydrodistillation in a Clevenger-type apparatus for 3 h, following the protocol of GonzalezMas (2019) and expressed as a percentage (w/w) of oil derived/gram dry weight of peel. Pectin content was determined by alcohol precipitation method using acidified

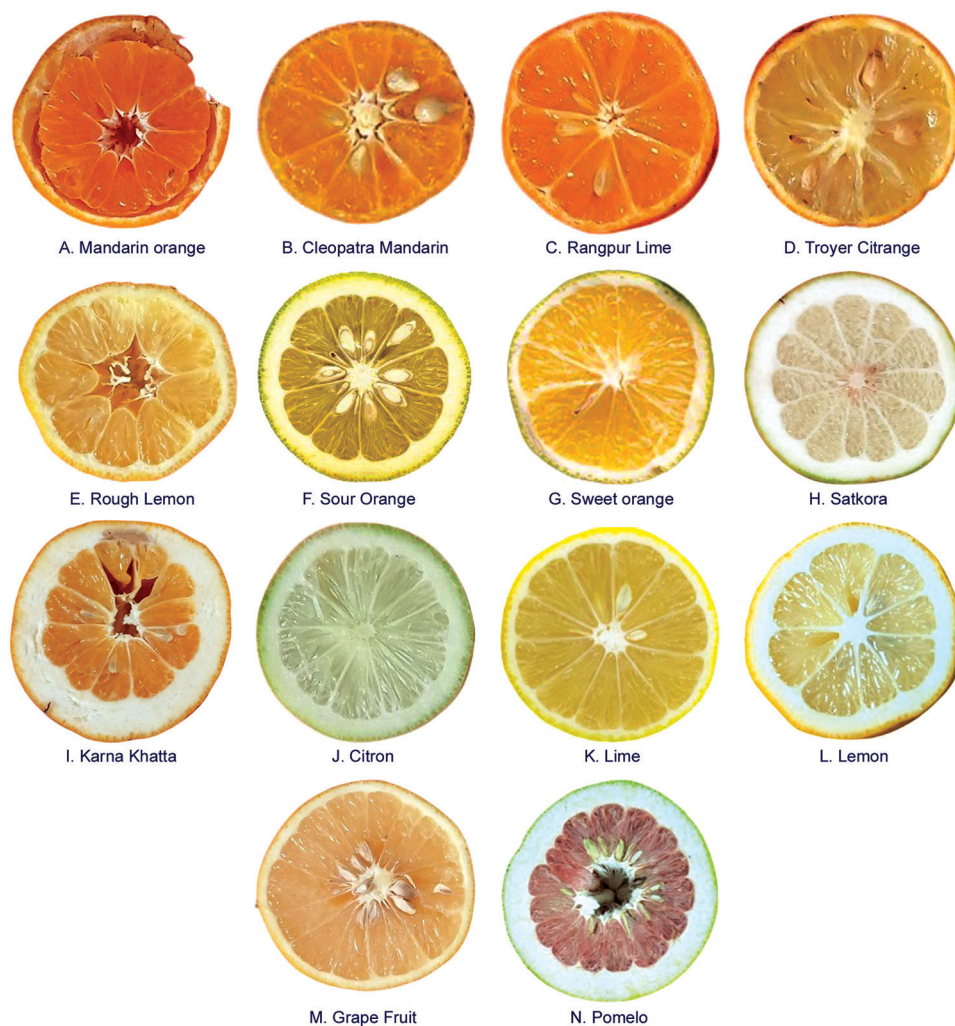


Fig. 1 Citrus fruits representing 14 distinct species.

extract of citrus peel, followed by gravimetric estimation as described by Ranganna (1986). The experimental layout followed a completely randomised design (CRD) with three replications for each species and the observed data were analysed statistically using SPSS software (version 26.0) for descriptive and inferential statistics, including analysis of variance (ANOVA) to identify significant differences at the 5% probability level (Gomez and Gomez 1984).

RESULTS AND DISCUSSION

Phytochemical composition of citrus peels: The present study exhibited significant variation in the phytochemical constituents of peels across 14 citrus species (Table 1). Total phenolic content, encompassing both free and bound phenolics, showed a wide range from 6.97 mg GAE/g DW (Rangpur lime) to 19.93 mg GAE/g DW (Grapefruit), indicating a high degree of interspecific diversity. Grapefruit (13.86 + 6.07 mg GAE/g DW), Pomelo (10.59 + 5.03 mg GAE/g DW) and Satkora (13.11 + 4.32 mg GAE/g DW) were particularly rich in phenolics, that might be attributed to their genetic makeup and environmental influences during fruit development. The predominance of free phenolics over bound forms aligns with the reports

of Rafiq *et al.* (2018), who expressed higher extractable phenolics in citrus peels when compared to other fruit peels. The variation in TPC can be justified by differential accumulation of secondary metabolites influenced by genotype, climatic conditions and maturity stage (Singh *et al.* 2020).

Total flavonoid content followed a similar drift, with maximum concentration observed in Pomelo (12.58 mg QE/g DW) and Grapefruit (9.66 mg QE/g DW), followed by Lemon (9.31 mg QE/g DW). These findings are in line with the work of Ghasemi *et al.* (2009), who reported citrus peel to be a potent source of flavonoids such as hesperidin and naringin. The interspecies differences in TFC may be due to varied biosynthetic capacities of flavonoids across citrus types, which are influenced by the gene expression involved in phenylpropanoid and flavonoid pathways (Burin *et al.* 2024). Flavonoids contribute significantly to

antioxidant and therapeutic potential, especially in citrus genotypes with thick, bitter peels such as Pomelo and Grapefruit (Wang *et al.* 2023).

Ascorbic acid of the citrus peel ranged from 72 mg/100 g FW in Karna khatta to 156 mg/100 g FW in Satkora, indicating citrus peel as a significant source of natural vitamin C. High vitamin C levels in Satkora and Citron are in line with previous reports (Czech *et al.* 2021), where wild and indigenous citrus types were found to accumulate more ascorbate due to oxidative stress adaptation and enhanced vitamin C biosynthesis (Sir Elkhatim 2018). The variation in vitamin C among species might also be linked to peel thickness and the presence of protective enzymes that reduce oxidation loss during fruit development and storage (Wedamulla *et al.* 2022).

The carotenoid content in citrus peels significantly varied among citrus species, ranging from 67.3–306.1 µg/g FW. Cleopatra mandarin exhibited the highest carotenoid concentration (306.1 µg/g), followed by mandarin orange (221.5 µg/g) and Rangpur lime (196.5 µg/g). In contrast, the lowest content was recorded in lime (67.3 µg/g). Notably, sweet orange, pomelo and grapefruit displayed moderate levels ranging between 100–150 µg/g. These variations

Table 1 Bioactive compound potential of peels of different citrus species

Citrus species	Phenolics content (mg GAE/g DW)			Ascorbic acid (mg/100 g FW)	Total flavonoid content (mgQE/g DW)	Antioxidant activity (% DPPH reduction)	Carotenoid content (μ g/g FW)
	Free phenolics	Bound phenolics	Total phenolics				
Mandarin orange	4.69 \pm 0.8	3.13 \pm 0.4	7.82 \pm 0.9	112.2 \pm 10.1	4.63 \pm 0.5	56.9 \pm 6.3	221.5 \pm 18.9
Cleopatra mandarin	5.22 \pm 0.7	4.19 \pm 0.6	9.41 \pm 1.2	98.5 \pm 8.7	4.14 \pm 0.3	51.2 \pm 5.1	306.1 \pm 23.5
Rangpur lime	4.61 \pm 0.9	2.36 \pm 0.3	6.97 \pm 0.7	78.9 \pm 6.9	5.92 \pm 0.7	47.8 \pm 4.6	196.5 \pm 17.2
Troyer citrange	8.23 \pm 0.7	4.49 \pm 0.6	12.72 \pm 1.3	98.6 \pm 8.6	4.16 \pm 0.4	52.3 \pm 4.8	172.3 \pm 14.7
Rough lemon	5.41 \pm 0.6	3.44 \pm 0.5	8.85 \pm 1.0	141.3 \pm 12.1	7.58 \pm 0.6	49.5 \pm 3.9	96.7 \pm 10.5
Sour orange	6.01 \pm 0.8	2.60 \pm 0.4	8.61 \pm 0.8	86.8 \pm 7.9	5.32 \pm 0.5	55.2 \pm 6.7	111.4 \pm 9.8
Sweet orange	11.34 \pm 1.2	5.03 \pm 0.7	16.37 \pm 1.8	139.5 \pm 13.0	8.40 \pm 0.7	63.0 \pm 6.9	135.8 \pm 11.5
Satkora	13.11 \pm 1.4	4.32 \pm 0.5	17.43 \pm 1.5	156.0 \pm 14.7	11.25 \pm 0.9	70.4 \pm 8.0	108.9 \pm 9.6
Karnakhatta	7.09 \pm 0.9	4.37 \pm 0.6	11.46 \pm 1.2	72.3 \pm 6.8	5.22 \pm 0.4	54.6 \pm 6.1	85.5 \pm 8.9
Citron	9.89 \pm 1.2	6.04 \pm 0.9	15.93 \pm 1.7	152.6 \pm 13.2	8.16 \pm 0.7	67.8 \pm 6.4	115.7 \pm 10.4
Lime	5.78 \pm 0.7	4.13 \pm 0.6	9.91 \pm 1.1	76.4 \pm 7.0	4.88 \pm 0.6	56.5 \pm 4.8	67.3 \pm 7.2
Lemon	8.55 \pm 0.9	5.04 \pm 0.8	13.59 \pm 1.5	132.8 \pm 11.5	9.31 \pm 1.0	64.9 \pm 5.7	83.6 \pm 9.7
Grape fruit	13.86 \pm 1.4	6.07 \pm 0.9	19.93 \pm 2.1	119.1 \pm 10.3	9.66 \pm 1.1	72.6 \pm 8.1	144.1 \pm 12.5
Pomelo	10.59 \pm 1.2	5.03 \pm 0.7	15.62 \pm 1.9	138.4 \pm 15.2	12.58 \pm 1.3	79.3 \pm 6.8	116.8 \pm 10.4
SEM \pm	0.34	0.15	0.71	2.5	0.21	1.64	8.7
CD ($p=0.05$)	1.01	0.46	2.13	7.5	0.63	4.73	26.2

may be attributed to genetic factors, pigment biosynthesis potential and peel pigmentation intensity. The high carotenoid content in mandarins indicates their potential for antioxidant-rich by-product utilisation. These present results were supported by earlier studies, which indicated higher carotenoid concentrations in mandarin varieties compared to other citrus species, primarily due to elevated levels of β -cryptoxanthin and violaxanthin in their peels (Wang *et al.* 2008, González-Molina *et al.* 2010). The significant differences observed confirmed that citrus genotype plays a significant role in carotenoid accumulation, which is predominant for nutritional and industrial valorisation of citrus peel waste (Addi *et al.* 2022).

Antioxidant potential and functional attributes: Antioxidant activity, measured by DPPH radical scavenging capacity (Table 1), was highest in pomelo (79.3%) and grapefruit (72.6%), correlating positively with their high TPC and TFC. The observed antioxidant potential line up with the reports of Gorinstein *et al.* (2004) and Bocco *et al.* (1998), who demonstrated that citrus peels have higher antioxidant activities over pulp due to concentrated phenolic and flavonoid constituents. Lemon (64.9%) and citron (67.8%) also demonstrated strong antioxidant effects, reinforcing the potential of citrus peel in combating oxidative stress.

The observed differences in antioxidant capacity might be due to the synergistic effects of multiple phytochemicals, including phenolics, flavonoids and vitamin C. The structural diversity and hydroxyl group availability in these compounds

play a significant role in hydrogen-donating and radical-quenching abilities (Rice-Evans *et al.* 1997). Peels with higher antioxidant activity, particularly those of Pomelo, Grapefruit and Lemon are important promising species for use in natural food preservatives, nutraceuticals and cosmetic formulations (Wedamulla *et al.* 2022).

Proximate composition and industrial relevance: Crude fibre content varied significantly, with maximum values in lime (12.6%), satkora (12.5%) and Mandarin orange (10.5%) (Table 2). These findings align with the results of Ledesma-Escobar and Luque de Castro (2014), who emphasised the potential of citrus peel as a dietary fibre source, particularly in the functional food development. High fibre content enhances intestinal health and contributes to bulk-forming properties in food formulations.

In the present experiment, the protein content of citrus peels has ranged from 3.79 g/100 g DW (Sour orange) to 7.78 g/100 g DW (Pomelo). The high protein level in pomelo might be due to its larger peel mass and greater retention of cellular proteins during drying. Such differences may also be influenced by varietal genetics, nutrient uptake efficiency and tissue density (Nateghpour *et al.* 2021). Ash content, an indicator of total mineral presence, ranged from 1.9% (Lime) to 4.4% (Satkora), while fat content remained relatively low (1.08–4.29%), consistent with the typically low lipid profile of citrus fruits and the results align with the findings of Czech *et al.* (2020).

Essential oil content in peels of citrus fruits varied between 0.95% (Rough lemon) and 2.96% (Citron),

Table 2 Proximate composition and industrial relevance of different citrus species

Citrus species	Crude fibre (% DW)	Protein content (g/100 g DW)	Ash content (% DW)	Fat content (% DW)	Essential oil content (% DW)	Pectin content (% DW)
Mandarin orange	10.5±1.3	5.70±0.6	3.1±0.3	3.82±0.8	2.24±0.5	28.4±2.9
Cleopatra mandarin	7.8±1.0	4.82±0.3	3.3±0.4	3.77±0.6	1.02±0.2	21.7±2.0
Rangpur lime	8.1±0.9	4.55±0.4	4.2±0.4	2.58±0.7	1.32±0.2	16.1±1.9
Troyer citrange	7.2±0.8	5.37±0.6	3.8±0.3	2.71±0.5	1.17±0.3	14.6±1.7
Rough lemon	8.3±1.2	5.06±0.5	4.0±0.5	1.69±0.4	0.95±0.1	22.2±2.5
Sour orange	6.9±0.7	3.79±0.4	4.2±0.4	2.53±0.5	1.11±0.2	17.8±1.8
Sweet orange	10.3±1.3	4.97±0.6	3.9±0.3	4.29±0.6	2.31±0.4	19.4±2.1
Satkora	12.5±1.5	6.88±0.7	4.4±0.5	2.43±0.5	1.02±0.2	17.3±1.8
Karnakhatta	8.4±1.0	4.09±0.4	3.5±0.4	2.27±0.4	1.55±0.3	19.7±1.9
Citron	7.5±0.9	5.14±0.4	3.8±0.4	4.16±0.5	2.96±0.4	16.9±1.9
Lime	12.6±1.2	5.77±0.5	1.9±0.2	3.03±0.4	1.87±0.3	21.4±2.2
Lemon	9.1±1.0	6.02±0.7	3.9±0.4	2.14±0.3	1.54±0.2	26.5±2.6
Grape fruit	8.2±0.7	6.23±0.6	3.7±0.3	1.11±0.3	0.98±0.1	23.2±2.5
Pomelo	9.7±0.7	7.78±0.7	4.1±0.5	1.08±0.3	1.01±0.1	25.6±2.8
SEM±	0.20	0.14	0.11	0.12	0.06	0.53
CD ($p=0.05$)	0.60	0.41	0.32	0.35	0.18	1.59

confirming the aromatic richness of citron peels. The maximum pectin content was noted in Mandarin orange (28.4%) and Lemon (26.5%), followed by Pomelo (25.6%). These values align with the work of Uysal *et al.* (2011), who reported citrus peels as sustainable sources of commercial pectin with gelling and stabilising properties. Citrus peels with high essential oil and pectin levels have important industrial implications in the formulation of cosmetics, jellies, bakery products and pharmaceutical carriers (Munir *et al.* 2024).

The compositional variability observed among citrus species is justified by a complex interplay of genetic, environmental and physiological factors. Genetic background primarily dictates biosynthetic capabilities for specific phytochemicals. For example, Pomelo and Grapefruit, known for their thick and aromatic peels, naturally accumulate higher levels of flavonoids and essential oils (Agarwal *et al.* 2022). Environmental factors such as temperature, soil type and water availability influence metabolite synthesis. As all fruits were analysed under uniform laboratory protocols, variability due to processing was minimised. Still, minor differences may be attributed to factors such as fruit maturity at harvest and drying efficiency. Comparatively, our findings confirm the reports of previous researchers who found similar biochemical richness in citrus peels (Ghasemi *et al.* 2009, Munir *et al.* 2024). The elevated antioxidant and fibre contents observed in indigenous species like Satkora and Karna khatta also highlight the untapped potential of underutilised citrus genotypes (Lalruatsangi *et al.* 2021).

Correlation analysis: The correlation study of the phytochemical and nutritional parameters of citrus peels revealed several statistically significant associations, highlighting the interdependency of key bioactive compounds contributing to the overall antioxidant and nutritional functionality of citrus by-products (Table 3). A highly significant and positive correlation was noted within total phenolic content and antioxidant activity ($r = 0.84^*$), suggesting that phenolics are one of the principal contributors out of the radical scavenging molecules of citrus peels. This finding is strongly supported by Gorinstein *et al.* (2004), who demonstrated that citrus peels, being rich in phenolics, offer superior antioxidant capacity compared to pulp tissues. The present findings also navigated a robust correlation between total phenolics and total flavonoid content ($r = 0.74^*$), indicating the co-existence and co-regulation of these two classes of secondary metabolites in peel tissues.

Additionally, total flavonoid content showed a highly significant correlation with DPPH antioxidant activity ($r = 0.86^*$), reaffirming earlier reports by Ghasemi *et al.* (2009), who identified hesperidin, naringin and rutin in citrus peels as key flavonoids with potent antioxidant and therapeutic functions. Protein content of citrus peels also showed a significant positive correlation with DPPH activity ($r = 0.77^*$) and total flavonoids ($r = 0.74^*$), indicating a probable functional role of peptides or protein-polyphenol complexes in modulating antioxidant responses, which agrees with the observations made by Yang *et al.* (2022). Ascorbic acid showed moderate to strong positive correlations with total

Table 3 Correlation analysis among the different characters of peel of various citrus species

Parameters	Free phenolics	Bound phenolics	Total phenolics	Ascorbic acid	Total flavonoids	DPPH reduction	Crude fibre	Protein content	Ash content	Fat content	Essential oil content	Pectin content
Free phenolics	1.00											
Bound phenolics	0.76*	1.00										
Total phenolics	0.98*	0.87*	1.00									
Ascorbic acid	0.62*	0.52	0.62*	1.00								
Total flavonoids	0.77*	0.52	0.74*	0.76*	1.00							
DPPH reduction	0.83*	0.71*	0.84*	0.63*	0.86*	1.00						
Crude fibre	0.21	0.03	0.17	0.20	0.30	0.31	1.00					
Protein content	0.57*	0.46	0.57*	0.56*	0.74*	0.77*	0.54*	1.00				
Ash content	0.37	-0.03	0.28	0.46	0.50	0.23	-0.39	0.04	1.00			
Fat content	-0.25	-0.05	-0.21	-0.01	-0.48	-0.31	0.08	-0.41	-0.30	1.00		
Essential oil	-0.02	0.26	0.06	0.17	-0.14	0.07	0.15	-0.17	-0.32	0.74*	1.00	
Pectin content	-0.07	0.11	-0.02	0.18	0.23	0.30	0.28	0.44	-0.29	-0.22	0.00	1.00

(*statistically significant at $p=0.05$ level of significance)

flavonoids ($r = 0.76^*$) and phenolics ($r = 0.62^*$), suggesting a cumulative and possibly synergistic antioxidant defense mechanism involving polyphenols and vitamin C (Zapata *et al.* 2024). Crude fibre content was positively correlated with protein ($r = 0.54^*$) and pectin ($r = 0.28$), suggesting that peels rich in structural polysaccharides may also have enhanced functional properties. Although fat content was comparatively less across genotypes, it has shown negative correlation with phenolics, flavonoids and antioxidant activity. Such correlations indicated that genotypes high in phytochemicals and antioxidant potential, such as pomelo and grapefruit, are ideal candidates for value-added processing in the nutraceutical, pharmaceutical and food industries (AmalaDev and Joseph 2025).

On the basis of the present study it could be concluded that, citrus peels exhibit a broad spectrum of phytochemical and nutritional attributes, varying significantly across species. These differences provide strong justification for targeted valorisation strategies, especially in functional food and nutraceutical industries. The high phenolic and antioxidant capacity of pomelo, grapefruit and lemon; the fiber-rich nature of lime and satkora; and the pectin and essential oil content in mandarin, lemon and citron collectively suggested that citrus peels, often treated as waste, can serve as potent bioresources for multiple value-added applications.

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